TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

SANTERI SUNI

IMPROVEMENT OF SHUTTLE AND LIFT POSITIONING IN AN AUTOMATED WAREHOUSE SYSTEM

Master of Science thesis

Examiner: prof. Jouni Mattila
Examiner and topic approved by the Faculty Council of the Faculty of Engineering Sciences
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ABSTRACT

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The focus of this master's thesis is to develop methods to improve shuttle and lift fine-positioning in a multi-level automated warehouse system. These methods are to be used in existing sites to improve system performance, as also in future site projects.

The multi-level automated warehouse system examined in this thesis study is provided for customer by the system supplier in order to increase efficiency of the warehousing operation. During the system launch, there have been some issues with shuttle and lift positioning, which has led to standstills. In order to ensure best possible perform of the system for the customer, the precision of the shuttle and lift positioning should be improved. This allows minimizing the downtime of the system, and gives customer best possible access to stored items.

System performance and error logs were monitored during this master's thesis work. This allowed identification of individual shuttles and lifts with fine-positioning errors. Operation of these storage retrieval machines were improved by sensor alignment, sensor replacement or with other procedures. As a result of this thesis work, several methods to ease sensor alignment or to improve the positioning process were presented.

TIIVISTELMÄ

SANTERI SUNI: Sukkuloiden ja hissien asemoinnin kehittäminen automatisoidussa varastojärjestelmässä
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Avainsanat: varastokeräilijä, logistiikka, valosähköinen anturi, etäisyysmittaus, läheisyysmittaus

Tämän diplomityön tavoitteena on kehittää sukkuloiden ja hissien hienokohdistusprosessin toimintaa automatisoidussa monitasoisessa varastojärjestelmässä. Kehitettyjä toimintatapoja ja tekniikoita on tarkoitus käyttää jo olemassa olevissa kohteissa, kuin myös uusissa projekteissa.

Tämän diplomityön kohteena oleva varastojärjestelmä on toimitettu asiakkaalle varastotoiminnan tehokkuuden parantamiseksi. Järjestelmän ylösajon aikana on kuitenkin havaittu joitain ongelmia sukkuloiden ja hissien hienokohdistuksen kanssa, mikä on lisännyt järjestelmän seisonta-aikaa. Jotta asiakkaalle voitaisiin varmistaa järjestelmän paras mahdollinen toiminta, tulee sukkuloiden ja hissien asemointia parantaa. Tämä mahdollistaa tehokkaimman käyttöasteen sekä parhaan saatavuuden varastotuotteille.

Järjestelmän toimintaa ja virhetilastoja tarkkailtiin tämän diplomityön aikana. Tämä mahdollisti viallisesti toimivien sukkuloiden ja hissien paikallistamisen. Näiden laitteiden hienokohdistuksen toimivuutta parannettiin anturien kohdistuksella, anturien vaihdolla tai muilla menetelmillä. Tämän diplomityön tuloksena kehitettiin useita menetelmiä niin anturien kohdistuksen helpottamiseksi sekä asemoinnin parantamiseksi.

PREFACE

This master of science thesis was done for the multi-level warehouse system supplier based on the need for improvement noted by the writer of this thesis and service technicians in Finland. In this thesis, theory, and improvement methods for positioning of storage and retrieval machinery are represented. In addition, theory of logistic automation is also covered.

I would like to thank for the opportunity to do this master's thesis work. Especially I am thankful for help and assistance from Jani Eronen and Desmond Currivan from the system supplier, and Jouni Mattila from Tampere University of Technology, who were supervising this thesis work. For technical assistance, I would like to thank Tobias Winter, as also service technicians in Finland.

Tuusula, 19.2.2017

Santeri Suni

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

A	Ampere
AC	Alternative Current
ADC	Analog to Digital Converter
AGV	Automated Guided Vehicle
AMR	Anisotropic Magneto Resistive
APS	Advanced Planning and Scheduling
DAC	Digital to Analog Converter
Data Highway Plus	Network communication protocol
CAN	Controller Area Network, a serial connection standard
CAN Bus	Controller Area Network serial bus
CPU	Central Processing Unit
DC	Direct Current
EMI	Electromagnetic Interference
ERP	Enterprise Resource Planning
eSM	Safety module for servo drives
Firewire	A serial connection standard
GaAs	Gallium Arsenide
GENET	Network communication protocol
Hz	Hertz, unit of frequency
I, i	Current
I^2C	Inter-IC Communication, a serial connection standard
IR	Infrared
IEEE-488	A parallel connection standard
I/O	Input/output
LED	Light Emitting Diode
LHD	Load Handling Device
MelsecNET	Network communication protocol
MFC	Material Flow Controller
MFS	Material Flow System
MHS	Material Handling System
mm	Millimetre
nm	Nanometre
ns	Nanosecond
OMS	Order Management System
PLC	Programmable Logic Controller
Profibus	Process Field Bus, a standard for fieldbus communication
Profibus DP	Network communication protocol
PTT	Pick To Tote
R	Resistance
RS232	A serial connection standard
RS422	A serial connection standard
RS423	A serial connection standard
S	Siemens, SI unit of electrical conductance
s	Second
SCM	Supply Chain Management
SOC	Subordinate Control, Order receiving controller
STO	Safe Torque Off, safety function for Lexium servo drive
t	Time

TIWAY	Network communication protocol
Tote	Box for items
U	Voltage
USB	Universal Serial Bus, a serial connection standard
V	Volt
VPN	Virtual Private Network
WLAN	Wireless Local Area Network
WCS	Warehouse Control System
WMCS	Warehouse Management and Control System
WMS	Warehouse Management System
Δ	Delta, differential
Ω	Ohm

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1. INTRODUCTION

This master of science thesis was made together with the warehouse system supplier in order to improve shuttle and lift positioning in a multi-level automated warehouse system. These methods may be used in commissioning work, as also with residence maintenance in existing sites. The particular warehouse system examined in this study is provided for customer's warehouse in Tuusula, Finland.

The system examined in this study is a scalable multi-level warehouse shuttle system. The multi-level warehouse consists of a steel framework creating racks for storing totes, shuttles moving horizontally along the aisles between racks, and lifts moving in vertical motion to provide totes to these shuttles. Outside the multi-level warehouse, the system uses conveyors to transport totes to picking stations, shipping, etc. Incoming goods are loaded into the multi-level warehouse system by using decanting stations, which provide empty totes for employees to decant these goods to.

Since system launch in June 2016, there have been some issues with positioning of the shuttles and the lifts. Fine-positioning procedures on some certain storage retrieval machines have functioned slowly or have caused occasional errors. In some cases, these errors have led to crashes with totes stored in the warehouse system. These crashes can possibly cause machinery breakdowns and loss of goods. The warehouse system is designed in a way, that single point of failure in a shuttle or a lift does not bring the whole system into a standstill. However, breakdown of a shuttle can reduce access to some certain items in the warehouse. Improvement of positioning procedure is therefore important to ensure best possible operation for the customer. Appropriate positioning is most critical at transfer points in the multi-level warehouse system, where totes are handed over from shuttle to a lift or vice versa.

The need for this improvement work was determined by using error statistics received from the system. These error statistics included all occurred errors on each section of the hardware, and downtimes resulted by these faults. The objective for this work is to define why these errors occur and how these errors and downtime can be reduced.

This master of science thesis work consists of theory on logistics automation and measurement technology, and practical partition about shuttle and lift positioning improvement. In logistics automation theory partition, different concepts and construction of logistics automation software and hardware are covered. Different layers of Warehouse Management and Control System software and Programmable Logic Controller are presented. Measurement technology theory focuses on distance, proximity and angular sensing technology that is concerning the problem with positioning and alignment of multi-level shuttles and lifts. In practical partition, the theoretical research work on measurement technology is put to use in order to find ways to improve operation of the shuttles and lifts.

This thesis is organized as follows. Second chapter, Automation in logistics describes different operations in logistic systems, as also system layouts in warehouse control. Third chapter introduces the multi-level warehouse system, and links different parts of system to theory. Fourth chapter covers theory of sensor technology, focusing on distance and proximity sensing with photoelectric sensors, as also angular position measurement. In fifth chapter these theories are applied to improve positioning performance of the warehouse system. Last chapter lists conclusions of this thesis study.

2. AUTOMATION IN LOGISTICS

Logistics is not only a modern-day case. Since people started working in communities, new ways to transport goods were needed. Growth of trading stepped up new innovations for transport and handling of goods. Today, the word logistics comprises many different functions in a supply chain, including manufacturing, storing and transportation. [7]

Today, the accuracy of logistic operations has become increasingly more important. *"Logistics has to provide the right quantities of goods most efficiently at the right place in the right order within the right time [7]"*. Higher standards and requirements for efficiency and precision of logistics operation has led to development of new automation systems.

Logistic center, or distribution center is a facility designed to store goods that are acquired usually from multiple different suppliers. These goods are stored in these facilities before sending for further distribution. There are five main processes for a logistic center: receiving, storing, picking, consolidating and shipping. Some preparation work might be needed when goods are received. Usually this means repacking goods in to storage totes. In storing process, goods are placed in a specified storage area. Goods are stored in this location until they are needed for picking. In picking process, needed goods are retrieved from storage and placed into order containers. When all order containers from single order batch are finished, a consolidation process begins, where these containers are combined into shipping containers (dollies, pallets, etc.). After consolidation, the goods are ready to be shipped for further distribution. [8,25]

For logistic centers, the logistic costs can be divided into four categories: Transport, distribution, interest, and performance costs. Transport costs include shipping costs from the sources to the logistic center, and distribution costs includes shipping costs from the center to the receivers (stores, mail order customers, etc.). Interest costs originate from tied-up capital in inventory. Costs caused by different functions within the logistic center are included in performance costs. [7]

Fast development in automation technology and pressures to reduce performance costs are increasing the level of automation in warehousing. This results in more complexity of warehouse design. The trend in logistics today is also moving from lower frequency, large orders towards higher order frequencies with smaller quantity of goods. Nowadays, a single item can be shipped instead of large bulk packages. [8]

The most common warehousing task that is automated is transportation. Usually it is implemented by using roller or belt conveyors. Conveyors provide appropriate performance for multiple different sizes of goods, totes, boxes etc. Conveyors are also easy to acquire and are relatively cheap. Downside of conveyors is that a failure in single point of conveyor can, in a worst case, stop the entire production in the warehouse. One option for transportation is to use autonomous roaming vehicles (or automated guided vehicles, AGVs). Movement of these vehicles is not restricted by warehouse infrastructure and one vehicle can easily be replaced in case of breakdown. This advantage decreases standstill time significantly compared to conveyor breakdown. [8]

According to Clausen *et al.* [4] one of the most challenging tasks to increase efficiency in is order picking. In manual warehouses order picking is very labour-intensive and it is also difficult to automate efficiently and is very capital-intensive. Design of order picking system is crucial part of warehouse design, as it can hugely effect on operating costs. According to Coyle *et al.* [5] operating costs of order picking can be up to 65 % of the total operating costs.

Operating performance of the order picking system can described with four parameters. Malmborg and Al-Tassan [19] described these four parameters: item features, storage equipment, system operating rules and physical configuration of storage area and load unit size. Sub parameters for following are:

Item features:

- Transaction demand levels
- Item space requirements
- Item assignment constraints

Storage equipment:

- Vehicle route
- Speed pattern
- Movement pattern

System operating rules:

- Picking strategies
- Sequencing

Physical configuration of storage area and load unit size:

- Height
- Depth
- Number of storage aisles [19]

If an accurate simulation of order picking system operating performance is needed (total space requirements, capacity and service level), correlation between these parameters must be accurate. [4,19]

2.1 Architecture of Warehouse Control

Requirements for warehouse control systems are specified by the customer, and they are usually quite unique. This leads to a higher complexity of warehouse control systems and therefore, reuse of the same system on a different project is difficult. Verriet *et al*. introduce in their study [8] a reference modular architecture for warehouse control. It is based on functional components, which can be configured by using structural and behavioural components.

Warehouse management and control system (WMCS) is used to control the operations inside warehouse. WMCS usually is a layered system from larger scale strategic control of enterprise resource planning (ERP) to a bottom layer, material handling system (MHS). As the ERP implements the strategic control part of the system. It is responsible for higher level management including warehouse stock management and order management. Order assignments and usable resources are controlled at planning level and task prioritization is controlled at scheduling level. Functional part of the system is controller simply with a warehouse management system (WMS) and section control by a warehouse control system (WCS). WMS basically controls material movement, storing and orders within a warehouse. Therefore, WMS records different warehouse transactions and has real-time data about warehouse inventory. Auto ID data capture (AIDC) technology is often used to track material movement throughout the warehouse. AIDC technology includes barcode scanners, RFID, and network technology. Individual processes are controlled with material flow controller (MFC, material flow system is also used, MFS). [8,25]

In Verriets *et al.* reference architecture [8] stock planners, that are connected to the ERP, are located on the planning level and they are mainly responsible for goods distribution. Device managers in scheduling level are responsible for defining available goods from the warehouse. These device managers are link from stock planners to physical device controllers in MFC level. Device managers are also responsible for sequencing order tasks received from stock planners and forwarding next task for device controllers. In MFC level, device controllers coordinate tasks at the material handling zones. These material handling zones physically execute planned warehouse tasks. Material handling zone can be for example warehouse shuttle or lift, conveyor or picking station. The hierarchical “tree” of the WMCS levels can be seen in figure 1.

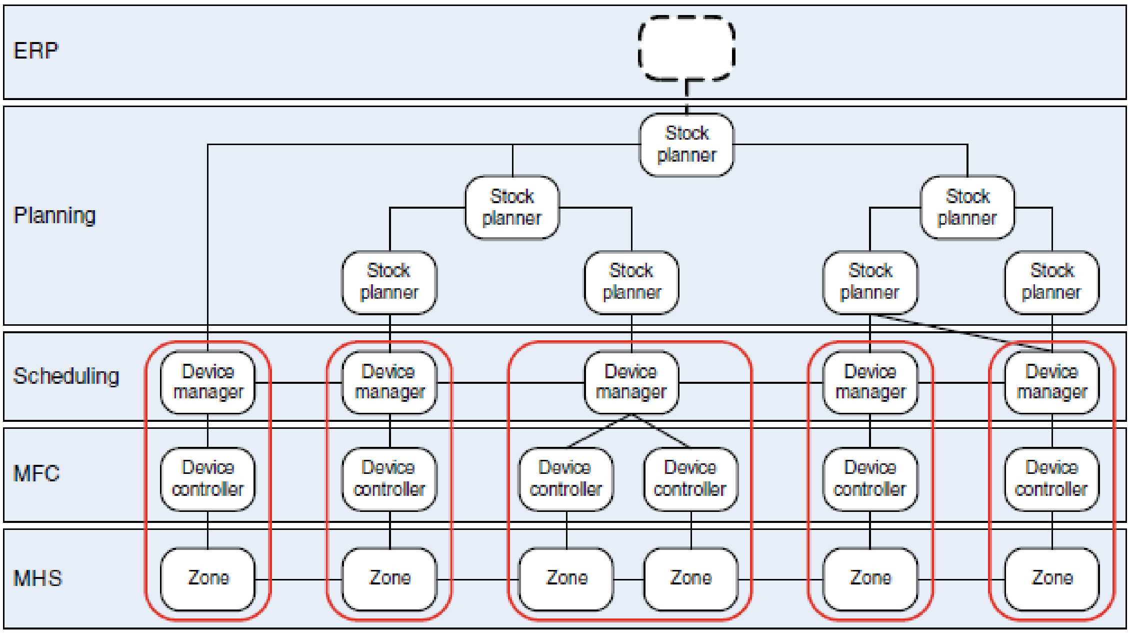

Figure 1. *Five layers of a warehouse management and control system in a reference architecture [8].*

Gudehus and Kotzab [7] introduced warehouse control and management in a three level hierarchical software system (figure 2). These levels are planning, scheduling and control softwares. Planning software is a higher level strategic control for planning, accounting, and administration. Gudehus and Kotzab [7] listed three software modules for planning level: advanced planning and scheduling (APS), enterprise resource planning (ERP) and supply chain management (SCM). These softwares are designed for resource usage and allocation. Scheduling level is used for inventory managements, allocation, order processing and handling and resource and performance monitoring. Control software is responsible for implementation of the actual operations and material handling.

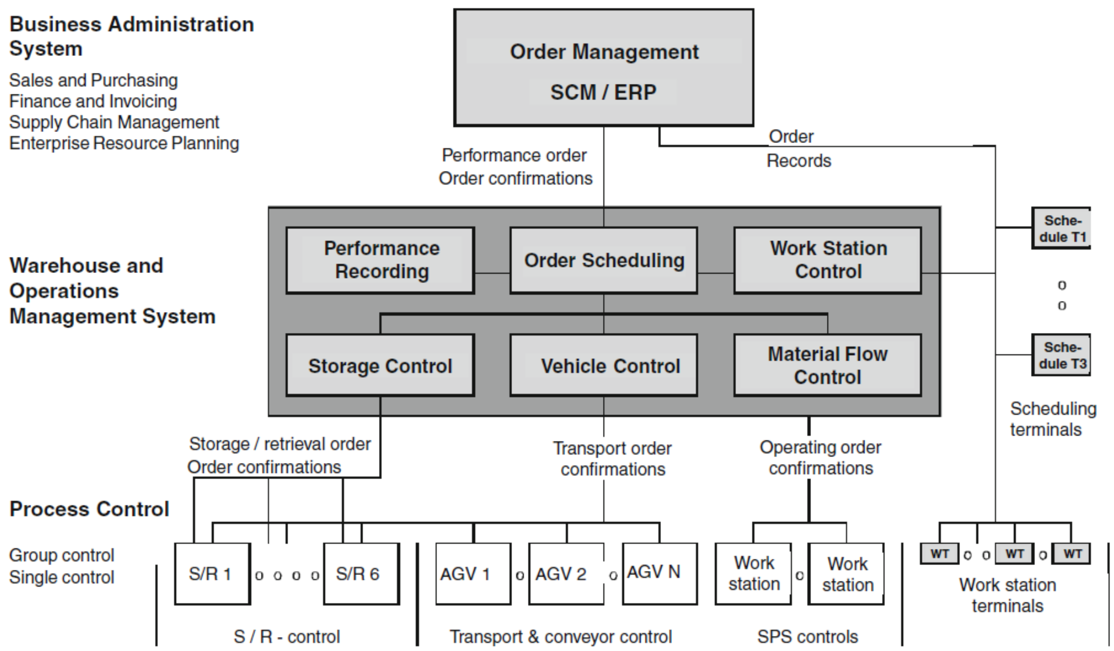

Figure 2. *Three level software hierarchy [7].*

Hierarchy of software levels is usually implemented in so called client-server-system. The server is responsible for executing central tasks and does the strategic planning. The server is also called the host computer. The client, or generally clients stores local data and executes local planning and control. Clients and host computer are connected via local area network. This allows all local stations to operate with the same data. [7]

2.2 Programmable Logic Controllers

Process control in hardware level is in most cases implemented with programmable logic controllers (PLC). Programmable logic controller has a programmable memory for instructions and function implementation. A microprocessor is used to execute these functions in order to control physical hardware. Typically, PLC programming is designed to be simple, and rather intuitive programming language is used. Therefore, special computer programming skills are not needed. Usually PLCs are pre-programmed for easy implementation at the destination site. The programming is primarily implemented with logic and switching operations, using simple *and*, *or*, etc. definitions. Information acquired from input devices, such as sensors, is used to implement predefined functions. Controls based on these functions are sent to output devices, such as electric motors, valves, lights, etc. [43]

Basic PLC controllers can be used with multiple different control systems. Control system modification is easy, as no rewiring is needed to change the used functions. Only new instructions of functions need to be defined. This allows flexible and cost-effective use and modification of control systems, when compared to old relay based systems. [43]

PLC systems consists of basic functional component elements. The power supply unit is used to supply needed low voltage direct current (DC) converted from alternative current (AC) voltage. Central processing unit (CPU) is responsible for fulfilling the control actions with microprocessor using the input signals. To execute these actions, CPU uses program stored in its memory. Needed programs are entered into the memory of the processor by using the programming device. The needed program is developed using this programming device and then transferred to the PLCs memory unit, where the programs and input data are stored. Input and output interfaces are used to communicate with input and output devices. These input and output signals can be discrete, digital or analog. When discrete or digital signals are used, the signal is either on or off (i.e. voltage or no voltage). Digital signals are similar to discrete, except that the signal can be sequenced. Analog signals are variable signals proportional to monitored value. The communication interface is used to transfer data with other PLCs and networks. [43]

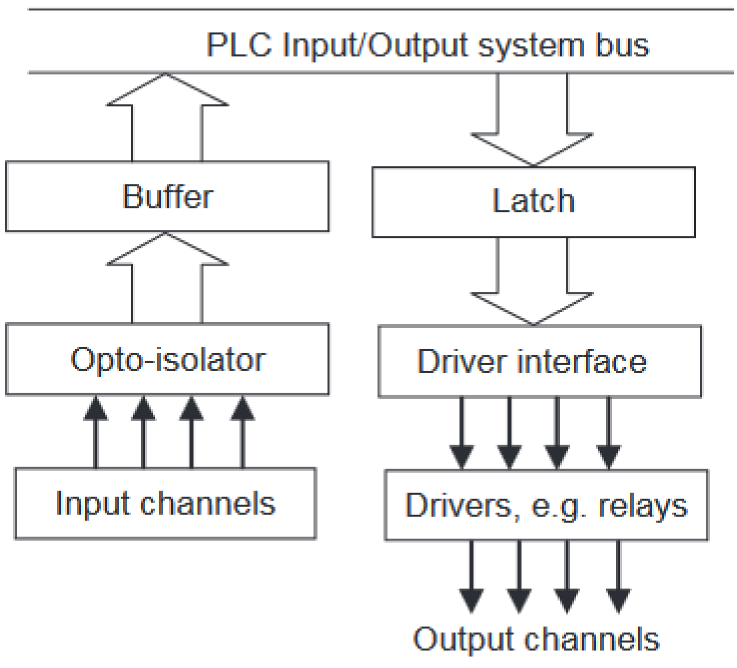

Figure 3. *I/O channels architecture [43].*

The connection between interface of the control systems and the physical hardware is implemented with a input/output (I/O) unit. The I/O unit enables connection to input and output devices through I/O channels (figure 3). The I/O unit is also used to enter programs from a program panel. To separate different I/O points, unique addresses (usually numbers) for these points are used. For example, Siemens SIMATIC S7 uses four character addressing in XYY.Z form, where X specifies if the module is input (=I) or output (=Q), YY stands for byte number and Z for bit number. Isolation and signal conditioning functions are provided with the I/O unit, allowing direct connection from sensors and actuators. Optoisolators (figure 4) are commonly used to achieve electrical isolation from the external world. Optoisolators use light emitting diodes (LEDs) to transform input digital pulses into infrared light radiation. This infrared light is received with phototransistor, that rises the voltage in the circuit. Electrical isolation is implemented with gap between LED and phototransistor. This signal conditioning allows use of wide range of different input signals to be used with the PLC. [43]

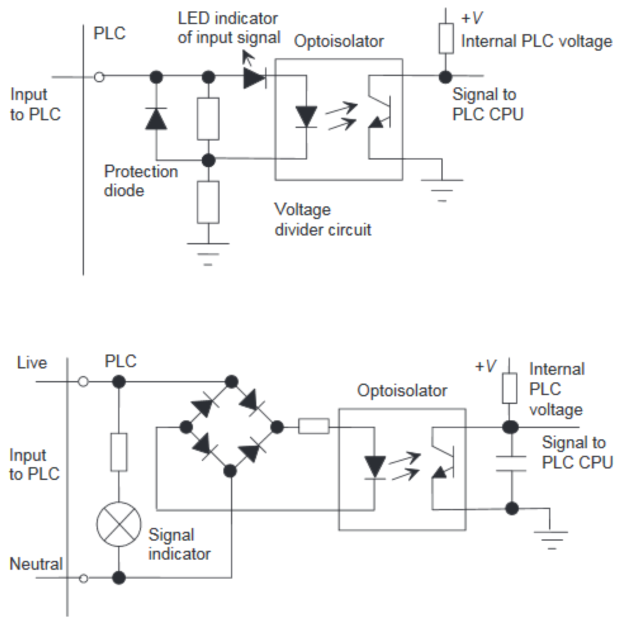

Figure 4. *DC (upper) and AC (lower) input units using optoisolators [43].*

A direct connection to external circuits is enabled from the output channels. Sourcing outputs provides current for the output devices, as the sinking outputs uses output devices to provide current to the output unit. These outputs can be relay type, transistor type or triac type. In the relay type output (figure 5), the relay is operated by using the signal from the PLC. This relay isolates the PLC from the external circuit, and is suitable for both AC and DC switching, and is also robust against high surge currents and voltages. [43]

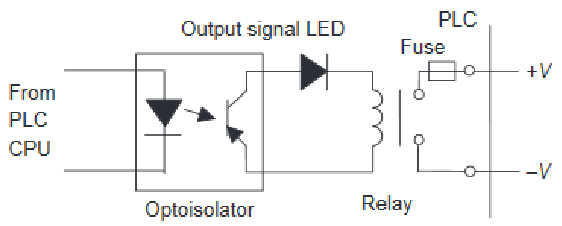

Figure 5. *Relay type output [43].*

In the transistor type output (figure 6), a current is switched through the external circuit using a transistor. Switching action is significantly faster than with the relay type output, but it can only be used with DC switching. The transistor type output is vulnerable to overcurrent and high reverse voltage and therefore, fusing or electronic protection is needed. Previously mentioned optoisolators are also used to provide isolation with transistor type outputs. [43]

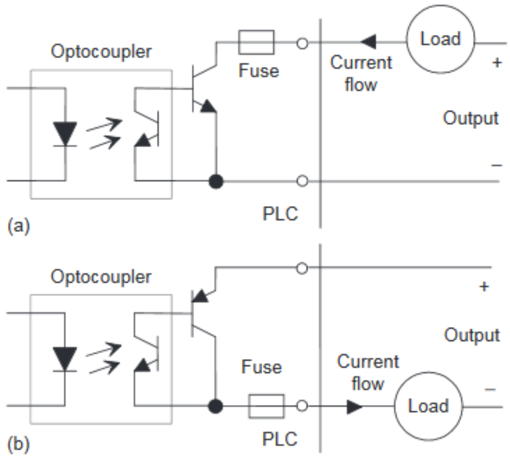

Figure 6. *Transistor type output, with a: current sinking and b: current sourcing types [43].*

Triac type outputs (figure 7) also use optoisolators. These outputs can be used to control actuators with AC power supply only and are vulnerable to overcurrent. Type of outputs varies with used PLC, and a range of different output types can be selected when using modular PLCs. [43]

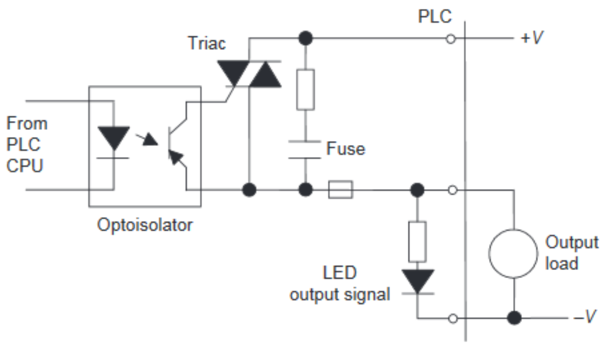

Figure 7. *Triac type output [43].*

The mechanical design of PLC systems is usually a single-box or modular type. The single-box type of design is used for small PLCs and usually has all the needed components integrated into a complete compact package. Number of inputs with single-box design PLCs usually varies between 6 and 24, as the number of outputs is between 4 and 16. Memory of the PLC is able to save 300-1000 function instructions. [43]

When larger number of inputs and outputs are needed, a modular designed PLCs are used. This kind of PLC has separate component modules that are fitted in racks. User can define the number of available inputs and outputs just by adding more I/O modules into the rack. Also, memory capacity can easily be increased just by adding more memory modules. The number of inputs and outputs per module varies between different type of rack chassis and modules, but are usually 8, 16 or 32 I/O per module. [43]

Analog input signals need to be converted into digital signals for the microprocessor. This is implemented by using analog to digital converter (ADC). Ready-made analog input modules with integrated ADCs are also available. ADC turns one single analog input signal into digital on/off signals using multiple output wires. Number of output signal wires determine the used numbers of bits. I.e. if the ADC has eight separate output wires and one wire has two states, on (1) and off (0). Therefore, the ADC has $2^8 = 256$ different output values. Different output values are achieved by combining the states of each output wire. As the number of bits affects to the range of different outputs, it also affects to the resolution of the ADC. The resolution indicates smallest possible change in input value, that changes the output value by one unit. Analog output signals are frequently needed and therefore, digital to analog converters (DAC) are needed for output channels. The working principle for DACs are the same as for ADCs, except for inverse conversion. Typical analog output values are 4-20 mA, 0-5 V DC, and 0-10 V DC, as also negative voltage values are also used. [43]

Digital data can be transmitted by using serial or parallel communication. In parallel communication, each bit is transmitted by one wire, and in serial communication only one wire using sequenced bit transmission is used. Serial communication is often used for long distances, because of less wiring needed. It is usually a standard for facilities with high level of automation. Used serial communication interfaces are RS232, RS422, RS423, I^2C (Inter-IC Communication), CAN (Control Area Network), USB (Universal Serial Bus) and Firewire. In parallel communications, the most commonly used standard interface is IEEE-488. [43]

Networks are used to connect all the computers and machines of the plant together. This communication network is called local area network (LAN). The forms of how computers/machines (terminal) are connected to the local area network are star, bus, and ring. In star form, each terminal is directly connected to the host computer. In bus form, each terminal is connected into a single cable, i.e. each terminal has direct connection to all other terminals. In ring form, a single terminal is connected to the next terminal with a continuous cable in a ring form. Range of different forms and methods of network system within PLC manufacturers varies. Profibus DP standard is used by Siemens and works in a star form. Data Highway Plus is used by Allen-Bradley and uses bus or ring forms. MelsecNET standard is used by Mitsubishi, GENET by General Electric and TIWAY by Texas Instruments. [43]

The data flow through LAN, either wireless or wired, does not have fixed delay. All analog information transformed into digital formation have certain distortion, and delay and variance occurs during transmission. For example, Profibus DP uses tokens to achieve relatively constant delay profile. With ideal conditions, wireless network can function just as well as wired network. In practice, this happens rarely, as there are multiple sources of interferences. [21]

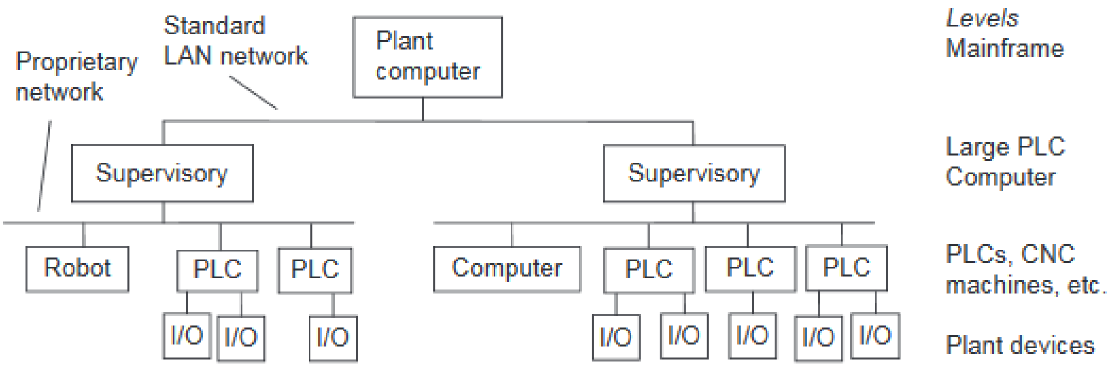

Figure 8. *Control hierarchy with PLC systems [43]*.

Plants with multiple PLCs usually follow hierarchy in control and communication, that can be seen in figure 8. At the bottom level are I/O devices, small PLC controllers are on the next level followed by larger PLC computers. Host computer is on the top level. [43]

3. THE MULTI-LEVEL WAREHOUSE SYSTEM

The studied warehouse is a multi-level form designed automated warehouse system. It is equipped with rack aisles in x-axis direction, each equipped with one or two shuttle systems. In each rack aisle, there are rack compartments located on both sides of the aisle. The storage goods are supplied to lifts using conveyors, that are located under the multi-level warehouse. These lifts load and unload conveyed material with load handling devices (LHD), and are responsible for providing these materials to different aisle levels. The material flow system defines desired aisle level for each transport unit. At the aisle, the transport unit is taken over by the shuttle, and is stored or received whenever it is necessary. [34]

3.1 The Multi-level Warehouse

Trend today is shifting towards a high bay style racking technology, because of its advantages in efficiency [44]. Automated multi-level racking systems for totes or pallets utilizes available space efficiently, ensures appropriate stock availability and makes process chains more efficient. The steel rack construction used in the multi-level warehouse system is developed and produced by the system supplier with high quality materials. Lack of welded connections ensures suitable tolerances for automated use. [37]

The axes of motion for the shuttles and lifts are following:

- X-direction: The horizontal travel of the shuttle along the rack aisle
- Y-direction: The vertical movement of the lift or the shuttle hoisting platform
- Z-direction: The horizontal movement direction of a load handling device telescope on the shuttle or on the lift [34]

The multi-level rack system can be build up to 24 meters high and rack aisles up to 150 meters long. This allows flexibility in rack design for different customer needs by adjusting the number or length of rack aisle levels. [35]

3.1.1 The Shuttle

The multi-level shuttle operates in x-axis direction along rack aisles, allowing tote transportation in and out of the storage racks on both sides of the rack aisle. Each rack compartment can store totes in two depths in four levels (exception: six levels on eighth floor in studied customer site). One or two shuttles can operate along one rack aisle. In this customer’s warehouse, only one shuttle is currently used, but an option for a second shuttle is available. The shuttle is equipped with a hoisting unit containing two LHDs. The hoisting unit allows movement upwards and downwards in y-axis direction. This makes storing and retrieving tasks possible on different rack levels on the rack aisle. LHDs are responsible for tote handling, as they transport totes in an out from storage racks and transfer areas in z-axis direction. All the movement directions of the shuttle can be seen in figure 9. [34]

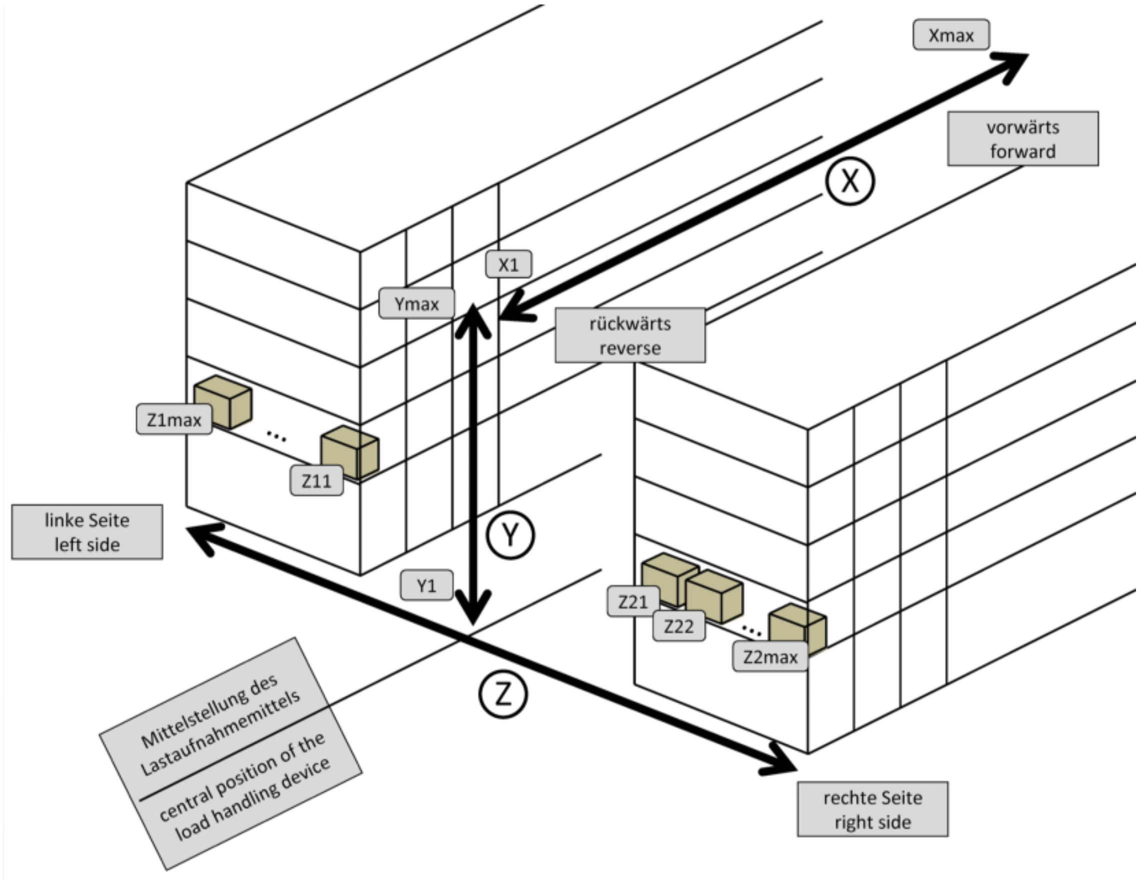

Figure 9. *Coordinate system of the multi-level shuttle [34].*

Load handling devices (figure 10) are able to do simultaneous storing and retrieval tasks on two different rack levels. This increases the efficiency of the multi-level shuttle system. One LHD is able to carry up to two totes simultaneously. LHD transfers totes from storage rack or from transfer position by using two telescopic arms (figure 11). One telescopic arm frame consists of three aluminium slides, that are connected to each other with linear bearings. Telescopic arm motions are implemented by DC gear motor and the power is transmitted by using toothed belt. When telescopic arms are extended to retrieve tote, flap fingers turn down and telescopic arms pulls the tote on to the LHD with these flap fingers. There are three flap fingers on one telescopic arm, six flap fingers total on one LHD. Flap fingers are operated by DC motors, and power is transmitted to the fingers by using planetary gears. [34]

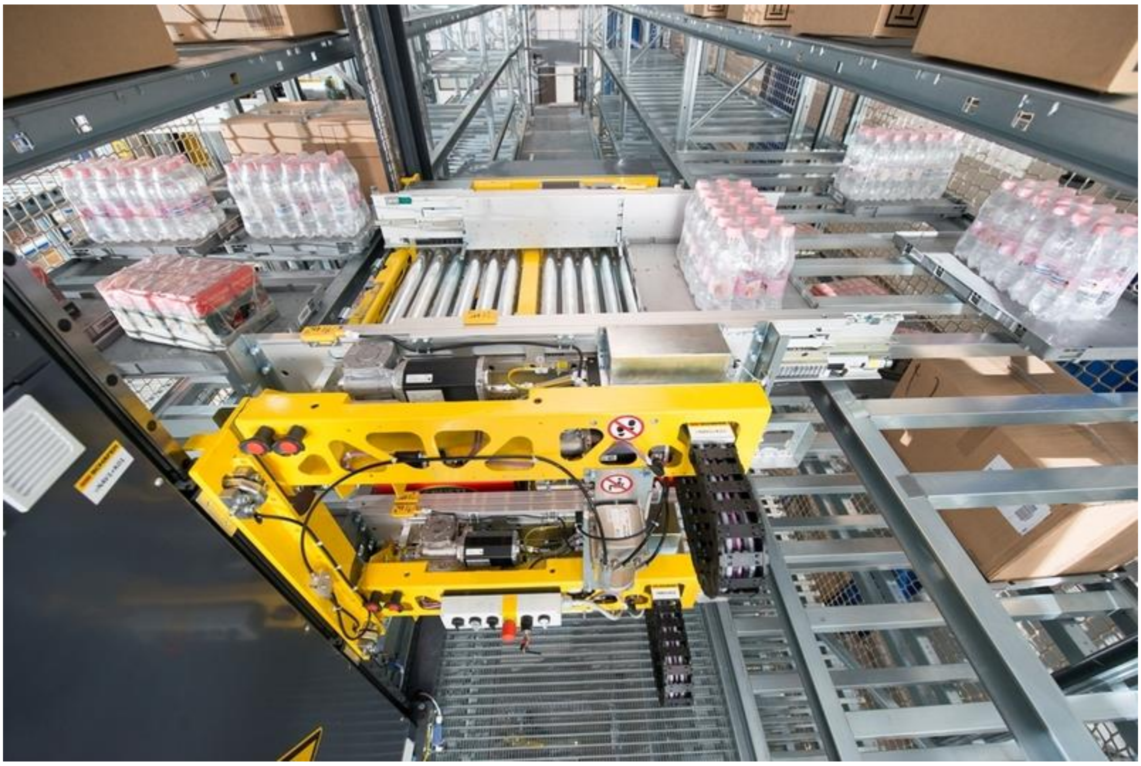

Figure 10. *Two load handling devices on a multi-level shuttle [35].*

There are 14 rollers on one LHD (figure 11), and these rollers are operated on two independent elements. One element is equipped with one motor roller and the power is transmitted to other six rollers with belts. A motor roller has an integrated brushless DC motor and is controlled with a motor roller controller. Motor rollers rotation direction can be adjusted, as well also rotation speed with a 0-10 V command signal. [34]

The gap between telescopes, and i.e. the gap between totes and telescopes (in x-axis direction) is operated with one DC motor and the power is transmitted via toothed belt. This belt is connected to both telescopic arms, i.e. separate x-axis movement of telescopes is not possible. Gap adjustment is necessary for some reasons. First, it allows use of different size of totes. Second, a larger gap between telescopic arms is used in retrieval tasks to minimize risk of crashes between the end of telescopic arms and totes. During storing tasks, a smaller gap is used for better accuracy. [34]

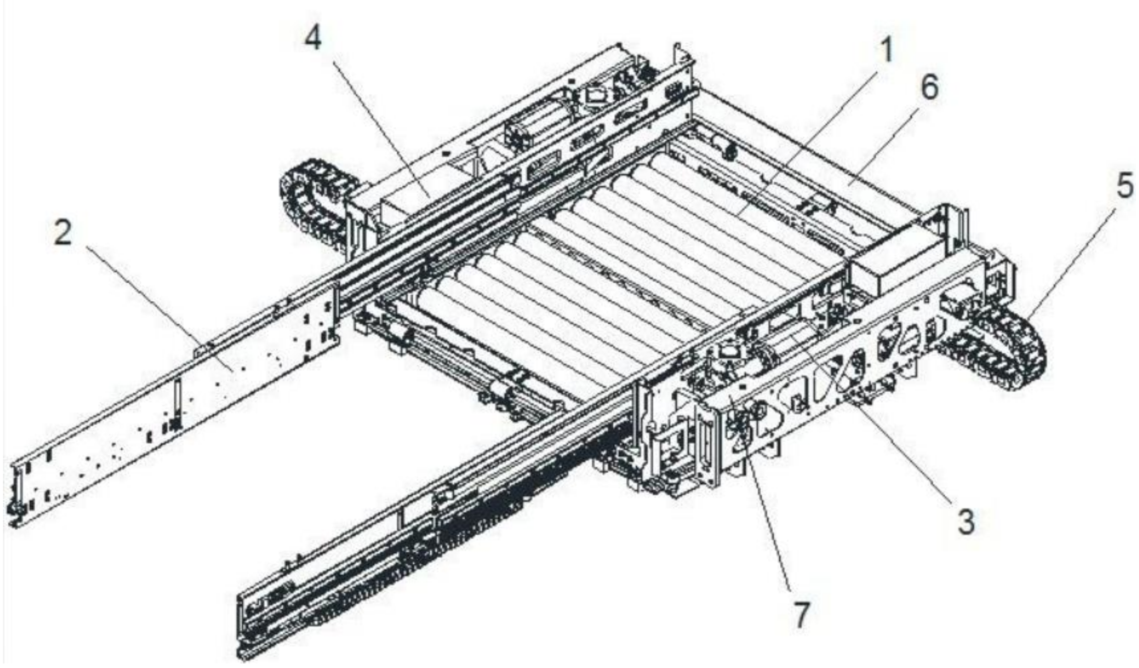

Figure 11. *Load handling device, 1: Roller conveyor 2: Telescopic arm 3: Gear motor 4: Terminal box 5: E-chain 6: Flap 7: Frame [34].*

During storing and retrieving tasks, the shuttle is dependent on information received from MFS about tote occupancy on its LHDs and different rack compartments along the rack aisle. As totes used in the warehouse are equipped with barcodes, there are no barcode scanners on LHDs. Because of this, shuttle's PLC is dependent on receiving reliable data from MFS. LHD can only determine the occupancy on each tote position (i.e. is the number of totes on board correct) on it by using retro-reflective photoelectric sensors, but is unable to identify nature of the occupancy. Therefore, disturbances in data flow, or if worker is manually moving totes, can cause errors on tote location in MFS. [34]

An industrial WLAN is used to enable data flow between shuttle and the PLC, as use of wired connection is difficult to implement. Power is transmitted to the shuttle with sliding contact conductor, containing three phases and a ground/neutral. [34]

The shuttle frame is supported by guide pulleys connected to upper and lower rail on one side of the rack aisle. There are four guide pulleys on the upper rail (figure 12) and four on the lower rail, total of eight guide pulleys. These guide pulleys are arranged in pairs so, that shuttle frame is supported on both sides of the rails. Levelling of the shuttle in z-axis direction is done by adjusting these guide pulleys. Therefore, wear on these guide pulleys also effect on level of the shuttle. [34]

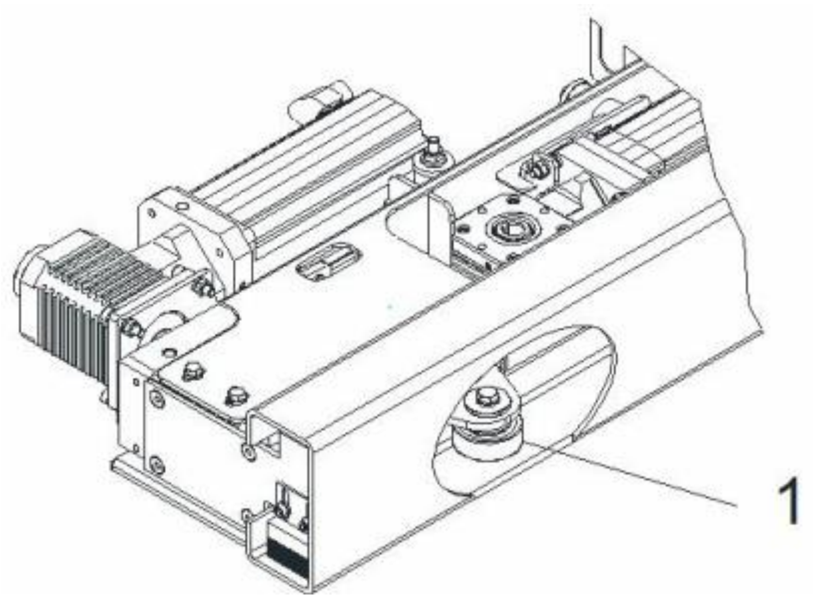

Figure 12. *Section of a drive unit from the shuttle frame. The x-master servomotor (left) and the y-drive servomotor can be seen. 1: Guide pulley inside rack aisle rail [34].*

The horizontal x-axis movement along the rack aisle is controlled with two servomotors. Power is transmitted by two running wheels, one on each servomotor. The needed gear ratio is fixed by a planetary gear. X-axis servomotors are controlled by two servo drives, the x-master and x-slave drives. Vertical y-axis movement of the hoisting unit is controlled by a single servomotor. This servomotor rotates spindle, that is connected to the hoisting unit, allowing it to shift upwards or downwards. Same type of servo drives are used for both x- and y-servomotors. A servo drive is controlled via Profibus DP, but other fieldbus modules are available. The servo drive has a safety function “Safe Torque Off” (STO) as a standard, but separate eSM safety modules are used in x-master and y-axis servo drives. These safety modules are responsible for operating speed control, and safe operation in local mode. Inputs from different sensors (limit switches, emergency stops, etc.) are communicating with this safety module. The x-slave drive does not have separate safety module and it is driven in command by the master drive. These servo drives are connected to each other with DC bus connection that makes braking energy reuse possible. [34]

The shuttle is equipped with external braking resistor, because of the kinetic energy that must be absorbed during quick deceleration exceeds the total of the internal proportions. Mechanisms that absorb braking energy internally are DC bus capacitor, internal braking resistor, and electrical and mechanical losses of the drive. Two values mainly determine energy absorption of the internal braking resistor: the continuous power (the maximum amount of energy that can be continuously absorbed) and the maximum energy (maximum amount of energy that can be absorbed short term). [34]

3.1.2 The Lift

The multi-level lift operates in y-axis direction transporting totes vertically to different levels. Inbound and outbound lines are located on the ground level under the multi-level warehouse system. In this case, both inbound and outbound are located on the same side of the lift, as inbound conveyor is located on top of the outbound conveyor. Each lift is equipped with one LHD with capacity to transport two totes at the same time. Maximum load is 35 kg per tote, 70 kg in total. Therefore, the lift is able to transport maximum of two totes at a time to four different rack levels on each rack floor level (exception: total of six rack levels of eighth level). This allows optimal allocation for different tote orders in and out from the multi-level warehouse. [34]

Structure of the lift is based on traditional counterweight lift structure, where weight of the counterweight is half of the maximum load capacity, 35 kg in this case. Counterweight is connected to a lift frame with two toothed belts. These belts are operated with a servomotor. This kind of counterweight structure allows the lift to run energy efficiently. [34]

The lift frame is connected to a lift mast with four freely running wheels. These wheels are connected to lift hoist platform with eccentric bolts, which allow levelling adjustment for the hoist platform. The other side of the platform is connected to a smaller supporting mast with two freely running wheels. The servo drive of the servomotor is located in the switch cabinet and the servomotor is located on the top of the multi-level warehouse. The data flow between PLC and lift is implemented by using long e-chain. [34]

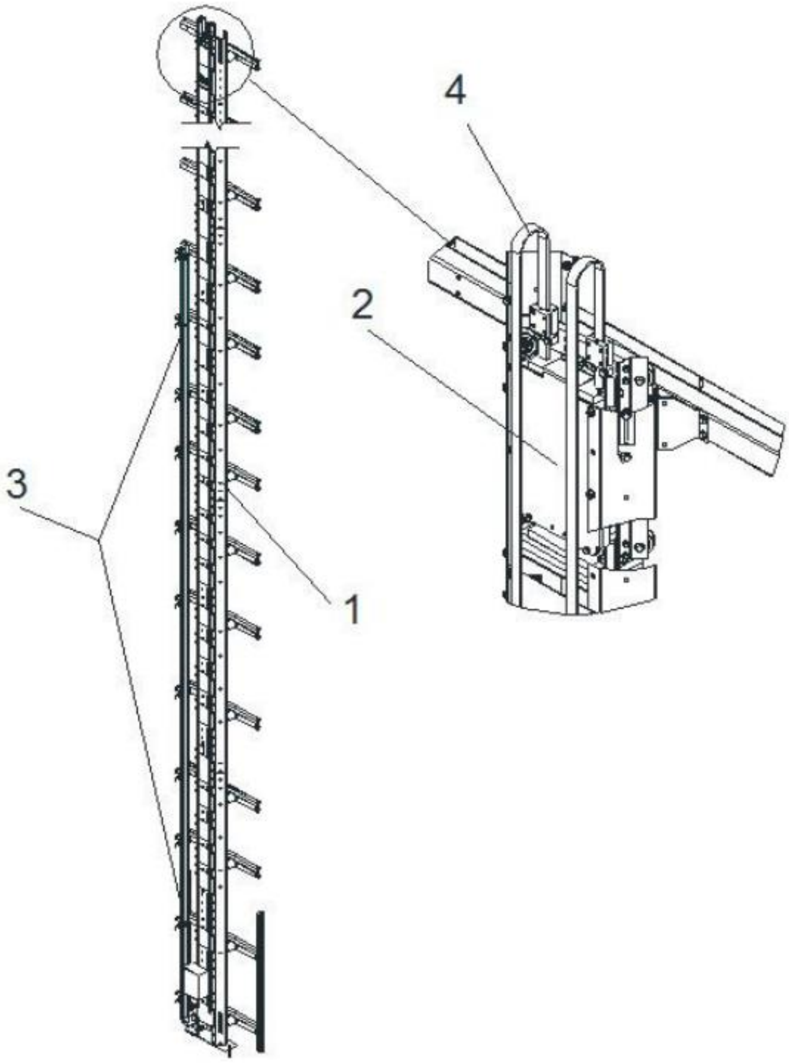

Figure 13. *Lift mast with attachments. 1: Mast 2: Counterweight 3: E-chain 4: Hoisting belt [34].*

Structure of a load handling device on the lift is similar to the LHD on a shuttle, except only one LHD per lift is used. [34]

3.2 Conveying systems

Totes are transported around the warehouse system via conveyors. A typical conveyor type is a roller conveyor. Rollers are powered with electric motors and power is transmitted with long belts. Pneumatic accumulators are used for switching connection between the belt and rollers on and off. In off mode, accumulators also brake the rollers for better tote handling, preventing them from touching each other. Accumulators are used only on a few rollers and power is transmitted to other rollers with short v-belts. With short conveyor lengths, rollers with internal DC motor are used. Belt conveyors are also used on some occasions. [38]

The layout of the conveying system is designed to for tote sequencing. System uses barcode scanners to keep track of each individual tote. By using this data, totes can be organized into right sequence at conveyor intersections. Special sequencer loops are used for more specific sequencing in consolidation orders. [31,32,38]

3.3 Picking stations

Picking in the warehouse system is done in batches using a goods-to-person picking method. In the goods-to-person picking method, order items are provided to employee via conveying system. Ordered goods (to the stores or online sales) are picked by employees at pick to tote (PTT) picking stations. PTT stations are able to handle around 750 order lines and 500 to 600 orders per hour. When an order is released to the WMS from the host, MFS starts to allocate storing totes for a right picking sequence. The sequence of the totes coming from the multi-level warehouse needs to be right, so that right products gets to the right shipping batches and therefore, to the right store/customer. Storing totes containing picking items are transported using upper conveyor and shipping totes by using lower conveyor of the PTT. The amount of picking items is shown to the employee on a display, as also picking items are illuminated. The item illumination makes picking easier on multi-compartment storing totes. Employee simply picks right number of items to the shipping tote. [36]

3.4 Decanting stations

Incoming goods are stored using storage totes at decanting stations. Decanting stations consists of two overlapping conveyors, and workstations for the employees. The upper conveyor provides empty storage totes from the multi-level warehouse, and filled totes are sent back to the warehouse using the lower conveyor. System calculates the volume and the combined weight of stored items and therefore, storage totes should not be overfilled. However, there are also over height sensors and a scale to ensure, that height and weight of the tote stays within limitations. [38]

Data of the decanted goods in each separate tote is saved to the system during the decanting. To function properly, the system needs accurate information regarding items physical size, weight, description etc.

3.5 Warehouse Management and Control System

Software system provided by the system supplier follows same kind of a hierarchical control system, as presented in chapter 2.1. Used softwares cannot be standardized in specific level, because of the reasons explained earlier, but processes for mapping logistics business processes are standardized. The system supplier uses modular design in software components. Therefore, these software modules can be reused in different projects with different customized configurations. Different modifications according to project specific needs are implemented by parametrizing the functionalities. This ensures tailored software for logistics needs of each customer, but still using the same standardized software framework. [32]

At the top of the hierarchy in the warehouse management and control system is customer's host system. Host system handles customer specific needs like order management, including invoicing, and planning of resources. Major part of the host system is the enterprise resource planning software. ERP has become standard requirement for basic business information processing. Similarly to other software components of WMCS, ERP systems are usually configurable module-based systems. [32,47]

Warehouse management system (WMS) communicates with ERP software in host level, and is responsible for controlling complex business process:

- Picking orders
- Partial inventory
- Material reordering
- Goods tracking [32]

WMS sends the order data to the material flow system (MFS) or warehouse control system (WCS). The warehouse control system is superior to the material flow system. It is responsible for handling groups of individual orders, and is used for picking and palletization business processes. Work orders are sent to WCS by WMS or OMS (order management system). Furthermore, WCS divides received orders into smaller orders and order groups which are sent to the MFS or in some cases, directly to the SOC (subordinate controller, order receiving controller). In System supplier's IT systems, WCS is a module part of the WMS. [32]

The material flow system controls individual transport units (totes, articles, cartons, pallets, etc.) by controlling conveying systems and other physical parts of the system. The MFS is responsible for routing the transport units through the warehouse using most efficient route along predefined routes. An order request is sent to the MFS from WMS or WCS, and the SOC is used for fulfilling these orders efficiently. Information flow between these softwares is continuous and therefore, each software component is aware of location of each transport units and product. [32]

The order receiving controllers forms the interfaces between the hardware and the software. Each SOC is responsible for specified and limited physical area. Programmable logic controllers (PLC) are used for controlling these parts of physical system. Siemens Simatic S7 PLC is used in this customer site. In some cases, PCX system can also be used. Visualization software called is used to display status, errors, and warnings of each separate PLC area. It is operated on virtual private network (VPN). [32,43]

4. SENSOR TECHNOLOGY

Precision in sensor technology mainly consists of terms accuracy, repeatability, and resolution (figure 14). Accuracy describes how close the measured value is to the real value. Repeatability is the closeness of individual measurement values of the same target to other measurement values. Good repeatability is essential with automated machine design. Repeatability can be different regarding on which direction the target point is approached. Therefore, repeatability can be measured uni-directionally (Target is approached from one direction), and bi-directionally, where target is approached from two directions. Third term, resolution, is the least significant change in value, that effects the measurement value of the sensor. [14]

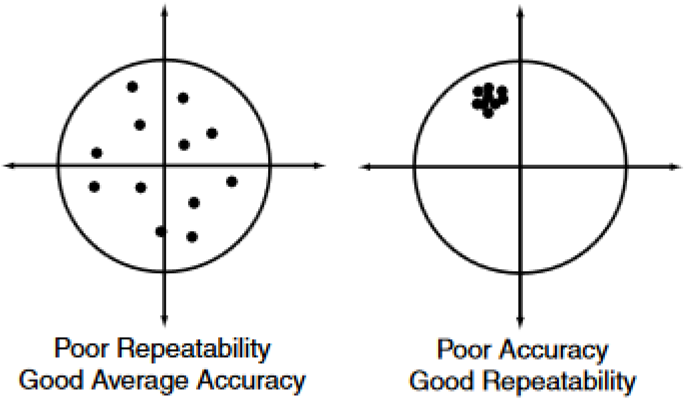

Figure 14. *Definitions of poor repeatability with good average accuracy, and poor accuracy with good repeatability [14].*

Besides the precision of the sensor, there are other factors effecting precision of the measurement. Alignment errors originates from misalignment between axis of measurement and measured object. Poor cable management can cause problems by conductor and insulation breakdowns, connector reliability, or by the drag force of motion. Appropriate thermal management ensures that, with temperature changes expanding and contracting materials will not affect measurement precision. [14]

4.1 Distance measurement

Devices for distance measurement can be generalized with some basic features. At first, distance measurement devices can be divided into contact or noncontact devices. Contact distance measurement devices are calibrated mechanical devices, that connects the measured point into a reference position. Very simple example of contact distance measurement device is a vernier caliper. Mechanical contact distance measurement methods are widely used in industry, for example in coordinate measurement machines. Disadvantages with contact distance measurement devices are restriction of measurement distance and slow measurement process. Technology with noncontact distance measurement devices is extensive. Accuracy of measurement in small distances with noncontact technology is inferior compared to contact technology, but measurement distances, speed and data quantity is superior. [42]

Noncontact distance measurement devices are based either on active or passive technology. With active technology, some form of controlled energy is used to create connection between reference point and sensing object. In most cases, the reference point is also the source of energy. In passive technology, an external source of energy is used, usually temperature contrast between sensing object and background. Active technology possesses better control over outside factors that interference measurement, as it has multiple choices of form and level of energy. This allows distance measurement through impenetrable materials, for example with ultrasound and x-ray measurement devices. Passive technology has its advantages in military application, since no energy is emitted and therefore the source cannot be detected. [42]

Noncontact distance measurement device technology principles can be divided into three categories: time of flight, triangulation, and field based. In time of flight technology, energy travels at a known speed (usually the speed of light). Time of flight system may be based on echo or active target type. With echo type system, travel time of energy emitted from a reference source and reflected back from the sensing object is measured. As the travel speed of energy is known, the travel distance can be calculated. Form of energy can be radiofrequency, light frequency or sound energy and devices are therefore called radar, lidar or sodar systems. With active target system, reference point emits energy and a separate receiver unit is used at the target point. Measurement error with time of flight technology is usually constant regardless of measurement distance. [26,42]

Triangulation is an old technology, that is based on trigonometry. Basic idea is that if length of one side and two angles of a triangle is known, length of remaining two sides can be calculated (figure 15):

$$R = \frac{b \sin \alpha_{left} \sin \alpha_{right}}{\sin\left(\alpha_{right} - \alpha_{left}\right)}$$

where R is the measured distance, b is the known baseline (distance between two known positions), α_{left} and α_{right} are angles of the known positions with respect to baseline. [42]

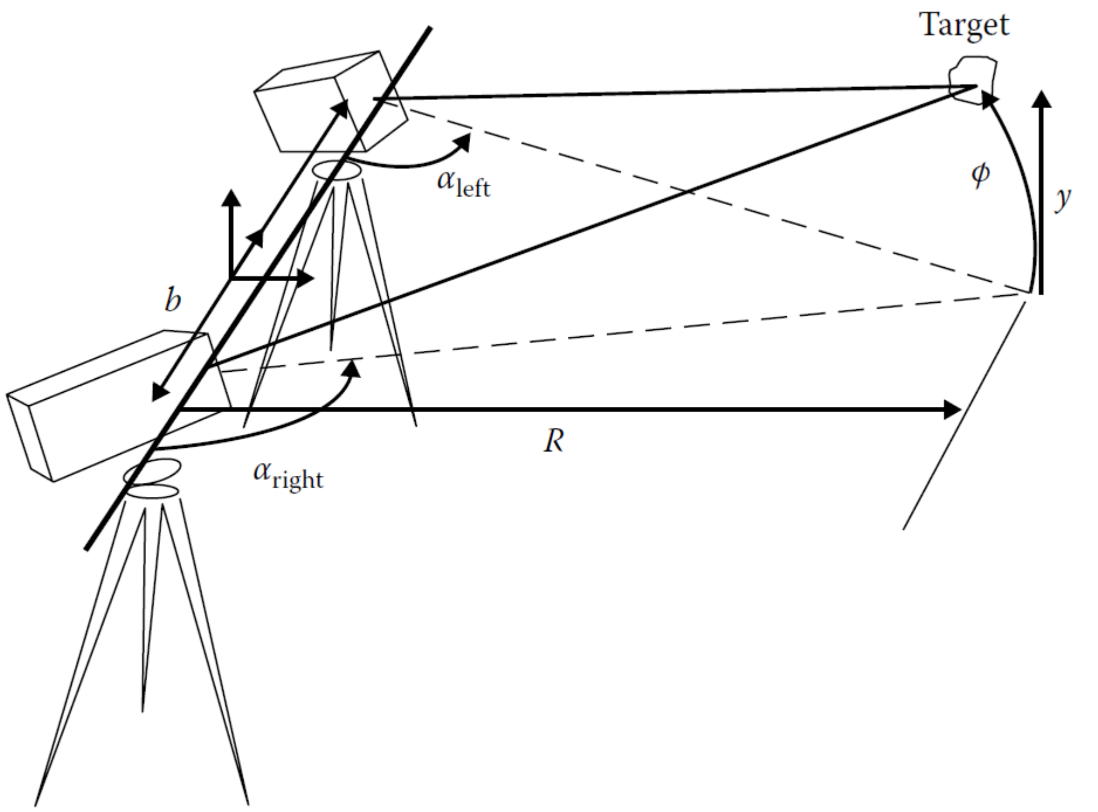

Figure 15. *The triangulation principle [42].*

Previous formula is used in passive triangulation technology, where target is monitored from two separate positions. Distance between these two positions is known, and it is called baseline. When baseline and angles between positions and target (in comparison to baseline), distance R can be calculated. In active triangulation technology, energy is projected from the reference position to target creating one side of the triangle. Axis from the receiver position to target creates second side of the triangle and therefore, baseline is the distance between reference position and receiver position. Triangulation technology has one major disadvantage when compared to time of flight technology, as precision of distance measurement decreases with square of the measured range. With short distances, triangulation technology overcomes time of flight technology in precision, but the advantage on precision turns to time of flight technology when measurement distance increases. [42]

Field-based technology uses spatially distributed form of energy, where the intensity of energy field changes as a function of measured distance. These fields have vector characteristics and if position of the source of energy field is known and spatial characteristics of the energy field are also known, distance between energy source and target can be calculated. However, field-based technology has some major disadvantages: Material or objects nearby usually interference energy fields and the magnitude of these interferences usually is not constant. In addition, like with triangulation technology, precision of distance measurement is strongly affected by measurement distance. That is, because energy field variation through space is highly nonlinear. [42]

All noncontact active technologies use some form of energy, regardless of measurement principle (time of flight, triangulation or field-based principle). Sound energy is usually used in time of flight type distance measurement devices, where echoed pulses of sound are measured. Frequency of sound used is usually in ultrasonic area, which is more directly focused. These ultrasonic frequencies are generated and received with piezoelectric transducers. Piezoelectric materials possess direct or indirect piezoelectric effect, where mechanical energy is converted into electrical energy or vice versa. Piezoelectric effect generates electric charge, which is explained in molecular level in figure 16. In figure 16a, material is not exposed to external stress and therefore, external effects of negative and positive charges are cancelled. In figure 16b, material is exposed to external pressure, causing its molecular structure to deform. This causes separation with positive and negative gravity centers and furthermore small dipoles are generated. In figure 16c, facing poles inside material are cancelled mutually, causing distribution of charge on the surface of the material (material is polarized). Mechanical energy, used to deform material, is generated into energy. With indirect piezoelectric effect, electrical energy is used to deform the material. [40,42]

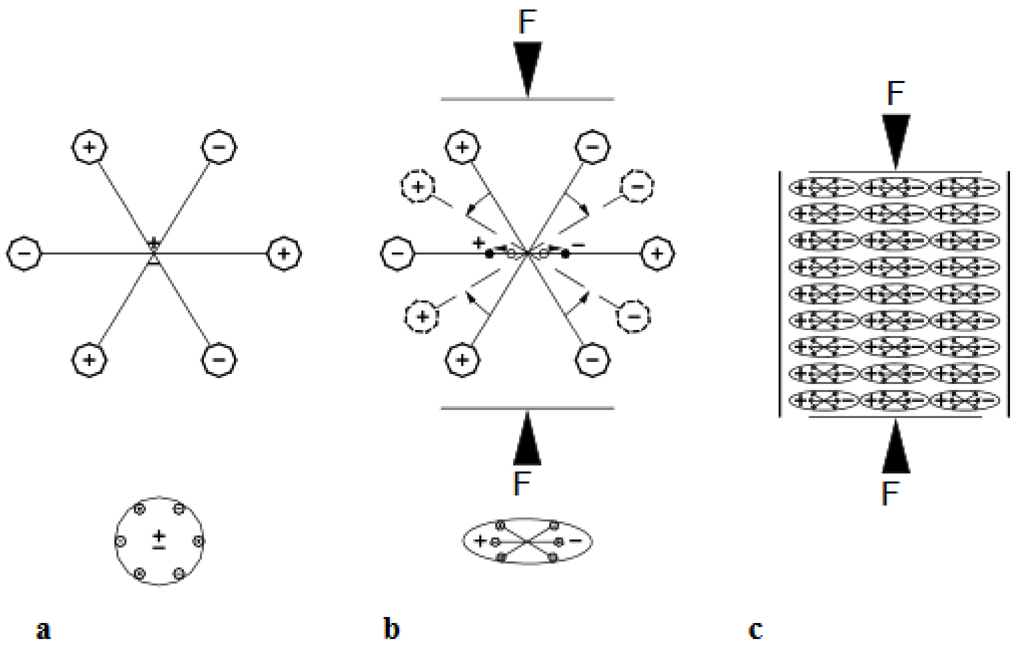

Figure 16. *Molecular behaviour of a piezoelectric effect [42].*

Ultrasonic signals travel through air, but transmission is much more effective in liquid. This has led to use of ultrasonic signals in underwater applications. Used ultrasonic frequencies usually range from 20 kHz into few hundred kHz. Disadvantage of sound energy when being compared to electromagnetic energy, is its speed variation depending on carrying material. Therefore, air humidity and pressure will affect measurement precision. [42]

Low frequency (stationary) magnetic fields are only used in field-based technology. They can be easily and cheaply produced with permanent magnet or electrical coil. Disadvantage for stationary magnetic field is the lack of transmitted energy and therefore active targets must be used. Electromagnetic spectrum in time of flight technology systems based on echo type that are between 1-1000 mm wavelength are radiofrequencies. These waves can be used for long distance measurement with different atmospheric conditions. Frequencies over radiofrequency in electromagnetic spectrum are light frequencies (infrared, visible or ultraviolet). These frequencies can be produced by laser devices and detected with solid photosensitive devices. Light frequencies are used with time of flight and active triangulation technology distance measurement. Active triangulation technology based distance measurement with light frequencies emitted by laser is illustrated in figure 17. [42]

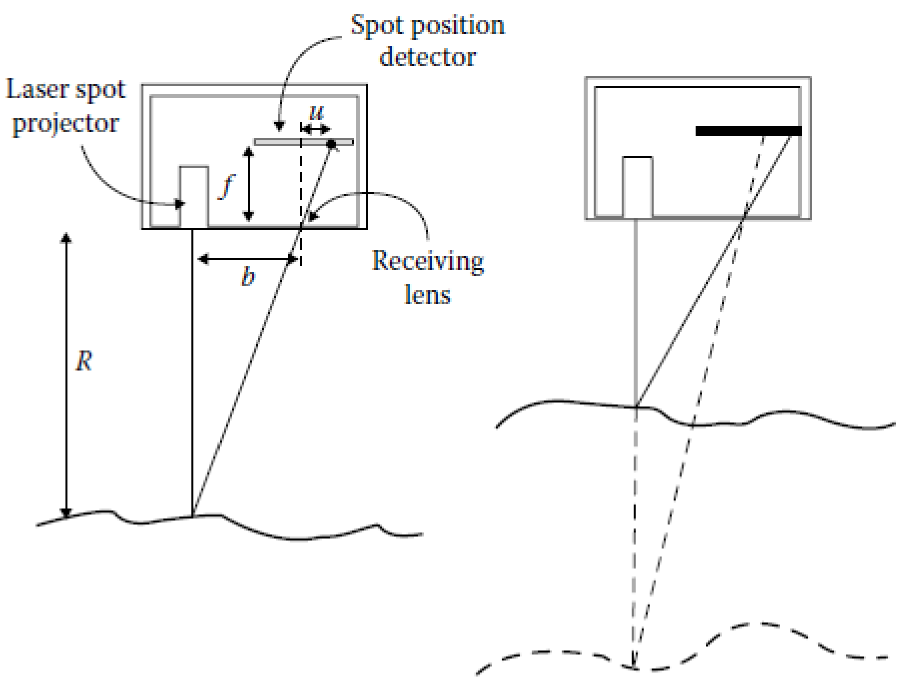

Figure 17. *Active triangulation technology based distance measurement with light frequency [42].*

In triangulation technology, measured distance is inversely proportional to the distance from the laser spot projector to the receiving point on spot position detector. Distance can be calculated with following formula:

$$R = \frac{bf}{u}$$

where R is the distance to sensing object, b is the baseline (distance between emitter and receiver), f is the offset from lens to detector and u is the reflection point on receiver. [42]

4.2 Proximity measurement

The main difference between distance and proximity measurement sensors is the length measured distances and, in some cases, orientation measurement of sensing object. Usually proximity sensors measure distances up to 50 mm and inclination up to ±30°. Proximity sensors are typically used in robotic grippers, when accurate distance and orientation is needed in near-zero values with high processing speed, usually 1…10 ms. [42]

Technologies used for proximity measurement are the same as for distance measurement, although currently electro-optical technologies are most used in robotic applications. Sensors with this kind of technology are relatively small and have large operation range. They are also robust against difference of material in sensing object. Also, ultrasonic and capacitive technology based proximity sensors are gaining support, as device sizes are decreasing. [42]

Operating principle with capacitive sensors is electrical capacitance measurement between two or more conducting materials (figure 18). This process occurs in dielectric (a nonconductor, which causes displacement of charge when applied with electric field, but does not generate flow of charge [15]) environment (air or liquid). High frequency wavelengths, usually over 100 kHz, are used for reduced impedance as the reactive impedance in air can be over 100 MΩ when audio frequencies are used. Capacitive sensors are used in proximity measurement for personnel and vehicle detection, as also in light switch modules for residential use. [2,30]

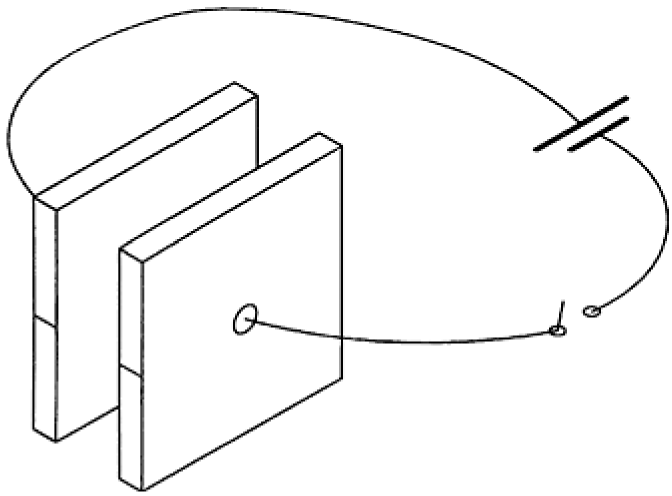

Figure 18. *Capacitive sensing [30].*

Inductive technology is based on penetration of electromagnetic field in the sensing object. This electromagnetic field is generated by coil with high permeability in the sensors core. An oscillator with high frequency excitation is used to minimize the penetration of the electric field inside conductive material. Sensing object generates its own electromagnetic field from reaction with electromagnetic field generated by the sensor (figure 19). This demands some specific minimum thickness and target size of the sensing object. Even smaller objects can be detected when sensors coil dimensions are reduced and driven frequency is raised. Demand for electrical conductivity in target limits sensing objects only to conducting metals. Reliable distance measurement with varying magnetic environment is also difficult. [13,30,42,49]

For optimal performance, the inductive sensor must be calibrated for different target materials, as their behaviour can vary considerably. Two basic types of target materials are ferrous and nonferrous. Ferrous materials are magnetic, such as an iron and most steels. Nonferrous materials consist of nonmagnetic metals, such as aluminium, copper, brass, zinc, etc. Inductive sensors are designed to work with either material, but sensors working with both materials also exists. Usual measurement distances for inductive sensors are between 0,5 mm and 15 mm, but other measurement distances are also achievable. Inductive sensors offer good resolution and frequency responses starting from 80 kHz. [45]

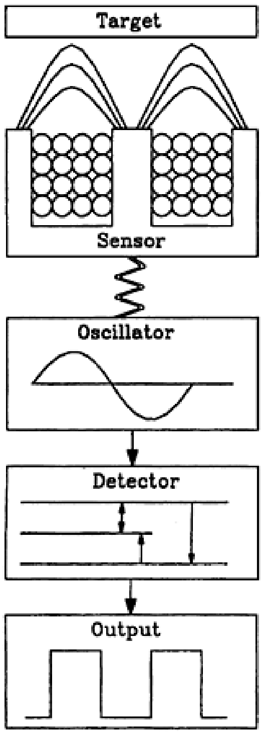

Figure 19. *Inductive sensing [30].*

Electro-optical robotics proximity sensing technology mainly uses light frequencies, that reflects from the surface of the sensing object by one or more following practices:

1. *"Single-surface reflection: Light waves that reflect specularly a single time off a planar microfacet, whose dimensions are significantly larger than the wavelength*

2. Multiple-surface reflection: Light waves that reflect specularly at least twice between multiple microfacets

3. Reflection after penetration: Light waves that penetrate into the material, refract, and then reflect back out as diffused light

4. Corner reflection: Light waves that diffract from interfaces with surface details about the same size or smaller than the wavelength (such as from corners of microfacets) " [42]

Electro-optical robotics proximity sensors, that use phase modulation usually have two light emitters and one or multiple receivers. Emitters are controlled with modulated sinusoidal voltage signals, with 90° phase difference:

$$V_1(t) = a \cos \omega t$$

$$V_2(t) = b \sin \omega t$$

where V_1 and V_2 are control voltages for emitters 1 and 2 with amplitudes of *a* and *b*. [42]

Receiver detects the signal, that is between of the two reflected signals, which suppressing (*A* and *B*) are corresponded:

$$V(t) = AV_1 + BV_2$$

where *V* is the voltage of the receiver. [42]

The combined received signal is:

$$V(t) = M \sin(\omega t + \phi)$$

where *M* is the combined function for suppression of the signal, and ϕ is combined phase shift. The combined function for suppression depends on geometrical and electrical parameters of the sensor, as also from objects orientation, surface quality and distance. [42]

Amplitude modulation technology used in electro-optical robotics proximity sensors, uses magnitude of the reflected light to determine the orientation of the sensing object. Amplitude modulation sensors usually have one emitter and several receivers. Received light intensity is inversely affiliated to the square of the measured distance. Orientation of the sensing object is calculated by using data on received light intensity on each receiver (figure 20). For both distance and orientation measurement, typically at least three receivers are needed. First receiver measures orientation in reference to second receiver and distance in reference to third receiver. [42]

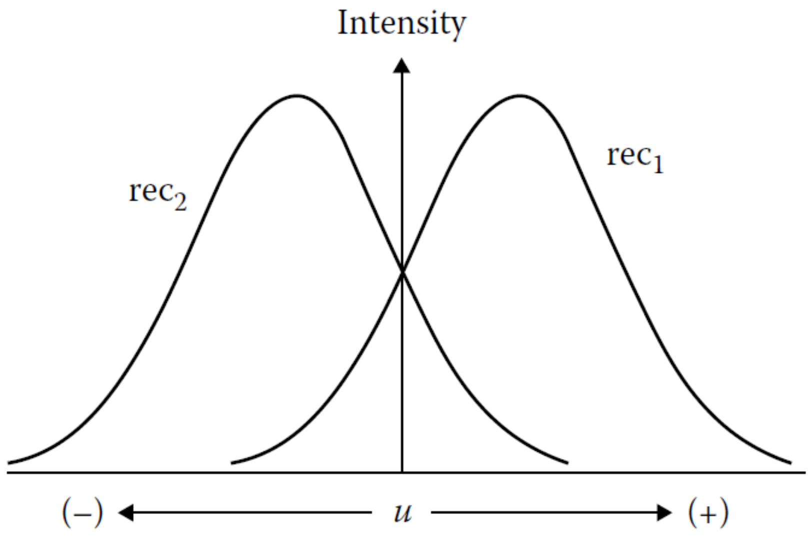

Figure 20. *Light intensity received by two receivers depending on the orientation of the surface on sensing object [42].*

In geometrical robotics proximity sensor technology, the orientation of the sensing object is calculated by using geometrical attributes of the reflected light. There are two geometrical technologies: triangulation, that was studied earlier, and Gaussian lens law based technology. In this technology, emitted light that is scattered from the surface of the sensing object is collected with a lens. Gaussian lens law is applied to calculate the distance of the sensing object, by using the focal of the lens and image position:

$$x = \frac{fw}{w - f}$$

where x is the measured distance, f is the focal length of the lens and image position is w. [42]

Likewise, with distance sensors, time of flight measurement technology is also used with proximity sensors. These sensors usually operate with modulated light beams and the measured distance is calculated by using phase shift of the reflection. Proximity sensors using time of flight technology are not usually able to measure orientation without additional systems. [42]

Photothermal effect technology uses similar signal processing methods as amplitude modulation technology. It uses strong light beam to create reflective thermal waves from the sensing object. The intensity of this thermal wave is used to calculate measured distance. Proximity sensors using photothermal effect technology are usually relatively slow and are inaccurate on sensing objects with high light absorbing surfaces. [42]

4.3 Angular measurement

An rotary encoder is a device used to measure angular displacement and provides digital output data. There are two kinds of encoders: the incremental encoder, that detects change in displacement compared to reference position, and the absolute encoder, that gives angular position as an output. The basic photoelectric incremental encoder consists of one fixed single aperture disk, one rotating multi-aperture disk, a light emitter and a receiver. Light is emitted through the slots of the disks from the emitter to the receiver and therefore pulsed output signal is created as the rotating disk turns. Resolution for incremental encoder is defined in counts per single turn. Very simple incremental encoders cannot define direction of rotation. Incremental encoders are used when only relative angular position is needed and are not usually used in servomotors. [6,43,45]

The absolute rotary encoder has certain pattern of slots in the rotating disk and therefore, angular position is uniquely defined. Therefore, each angular position gives unique output. Photoelectric absolute encoder has multiple unique slot tracks on rotating disk, as also multiple receivers. The rotating disk produces digital output code, known as Gray code (figure 21). Gray code is a binary numeral system that differs from normal binary system. In Gray code, each successive numeral value differs only by one bit and therefore, maximum error is only half bit. [6,45]

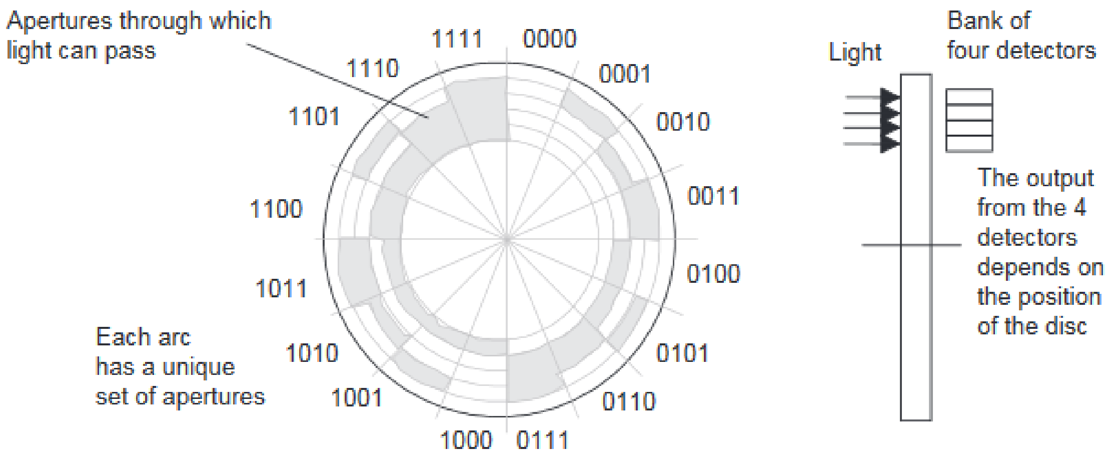

Figure 21. *Gray code used in an absolute encoder [6].*

Multiturn photoelectric rotary encoders measure rotation over multiple revolutions. This is implemented by using either geared or gearless design. In geared design, multiple shafts with gears are used where each shaft gear is moving the following shaft gear. Each shaft has its own etched disk which rotation is measured. Output of all rotating disks are combined in order to count total number of shaft turns. [45]

Magnetic rotary encoder uses passive variable reluctance or magnetized strips on a rotating disk which is sensed by the sensor, which is magneto resistive or Hall-effect type.

Magneto resistive sensor senses magnet angle by using field vector in the chip plane by using anisotropic magneto resistive (AMR) effect:

“The AMR effect is a "resistor" effect based on the dependence of electrical resistance on the angle between the directions of the current flow and magnetization of a ferromagnetic material. An external magnetic field can switch the internal direction of magnetization of the AMR material and thus effect changes in resistance (ΔR/R) that are typically on the order of a few percent.” [24]

In Hall-effect, electromagnetic field is generated within a conductor or semiconductor [15]. When strong transverse magnetic field is present, a flow of current occurs through [15]. Magneto resistive sensors have high sensitivity and a large operating distance from the magnet is possible. Angle measurement is limited to maximum 180°. Hall-effect sensors do not have as desirable sensitivity and operating distance as magneto resistive sensors, but Hall-effect sensors can measure angles up to 360°. [24,45]

Inductive rotary encoders measure reactionary current flow resistance to nearby materials by using one or multiple coils. Inductive rotary encoders has the same working principle as resolvers. They are equipped with a stator and a rotor. The stator is powered and send the output signal, as the rotor is passive. Usually the stator output is absolute angular position signal. [9,48]

One more common way to measure degrees of rotation is to use resolver. Basic structure of resolver is similar to electric induction motor. It is equipped with windings on the stator and a rotating rotor. A reference winding is located in the rotor and two secondary windings are located in the stator. The secondary windings are called sine and cosine windings, and they are displaced in 90° phase from each other. When the rotor is rotated, magnitude of energy travelling through windings varies sinusoidally, depending of the angular difference. The output voltage from the rotor reference winding is proportional to sine function. Difference of resolver compared to encoders, is that the output signal is analog. [1,9]

4.4 Photoelectric sensors

Photoelectric sensors are designed to detect objects and distances. They are also able to sense difference in surface conditions. Photoelectric sensor consists of an emitter that emits the light and a receiver that receives the light. Structure of an emitter and a receiver depends on the type of the photoelectric sensor. In a through-beam sensor, there is a separate receiver module facing towards the emitter. In retro-reflective sensor, a retroreflector element (a mirror) is used to reflect the light back to the receiver located in the same module as the emitter. Third type of photoelectric sensor is a diffuse-reflective sensor, that also has an emitter and a receiver elements on the same module. The light is reflected to the module from the sensing object. The main difference between these sensors is that on through-beam and retro-reflective sensors the sensing object interrupts the light, whereas in diffuse-reflective sensors the sensing object reflects the light. [22]

4.4.1 Diffuse-reflective sensors

Photoelectric sensors with adjustable distance setting (usually diffuse-reflective sensors) works based on a triangulation principle (figure 22). In triangulation, diffused light reflects back from the sensed object. [22]

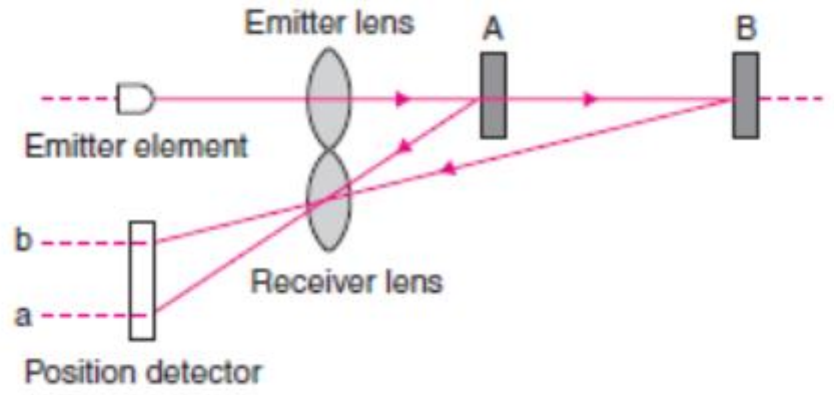

Figure 22. *The triangulation principle. Output of position detector (semiconductor) depends on where the light hits [22].*

Light sources for light emitters used in photoelectric sensors varies. The most common light emitter types are thermal light bulb, light emitting diode (LED), semiconductor laser, solid-state laser, and gas laser. Thermal light bulbs are cheap, compact, and easily available. They have wide optical spectrum and beam angle but small bandwidth and therefore, slow change in light intensity. LEDs are based on GaAs (Gallium arsenide, a compound used in semiconductors [10]) and 3-5 other compounds. LEDs cover all colours of visible and infrared light. They have narrow spectrum emission, but light intensity is electrically controllable. Semiconductor lasers, also called laser diodes, are also based on GaAs and 3-5 other compounds and has same kind of properties as LEDs. With laser diodes, light emission is implemented by using laser stimulation achieved with injection of charged particles. Solid-state lasers are expensive and used whenever large optical power is needed. Laser stimulation is implemented by using light pulses. Solid-state lasers have very narrow optical spectrum in visible and infrared area, narrow light beam and intensity controlling is difficult. Gas lasers use He-Ne (A compound of helium and neon [27]) and Ar (Argon, an inert noble gas [27]) gas. Laser stimulation is implemented by using gas discharge. Gas lasers have very narrow optical spectrum in visible and infrared area, narrow light beam and intensity controlling is difficult. [26]

Also, types of light sensors used in receivers varies. Most common types of light sensors are photoresistor, photodiode, photo transistor, diode array, position sensitive diode

(PSD), CCD (Charge-Coupled Device) camera, and CMOS (Complementary Metal Oxide Semiconductor) camera. [26]

Photoresistor has a photoconductor between two contacts, which resistance changes when it is exposed to a light. This phenomenon is called photoconductivity. This phenomenon occurs when semiconductor material is absorbing photons. Photoresistors can be divided into two categories: intrinsic photoresistors and extrinsic photoresistors. With intrinsic photoresistor, photoconductive material is excited of charge carriers from the valence band to the conduction band. With extrinsic photoresistor, charge carriers between impurity and the valence or conduction band excites the photoconductive material. [23]

When photodiode technology is used, the reflected light is concentrated with a lens of the receiver on a semiconductor. The semiconductor is a crystalline solid, which electric conductivity is located between a conductor and an insulator. Typical electrical conductivity value for semiconductor is $10^{-7}\ldots10^{5}$ S/m (siemens per meter), which is equivalent of $10^{5}\ldots10^{-7}$ Ω in electric resistivity. Semiconductors used in position detectors are called photodiodes, that are semiconductor diodes, which electric conductivity changes when exposed to light [3]. When photodiode is illuminated, the current increases proportionally depending on the amount of light [15]. 2-part photodiodes can also be used as a position sensor element. In this case, the receiver has two photodiodes and the sensor calculates the difference on light intensity between these two photodiodes. Advantage with 2-part photodiodes is its robustness against surface condition and colour changes of the sensing object as well the background does not greatly affect its operation. In both cases, the semiconductor in the receiver element gives different output signal depending where the reflected light hits. [22,27]

A diode array consists of number of photodiodes in array formation. A position sensitive diode is sensitive to the light intensity and the hit position of the light beam. The photo currents change proportionally with the hit position of the light beam. [26]

Phototransistors are photosensitive transistors, that are like photodiodes but are more sensitive to the light, because of internal amplification of primary photoelectric current. [15]

CCD and CMOS cameras are used to perform imaging tasks, and commonly used in mechatronics and robotics. Usual pixel size for these cameras are 5x5 micrometres. CMOS cameras have higher resolution compared to CCD cameras. [26]

Limited-reflective sensors working principle (figure 23) is same as for diffuse-reflective sensors. Emission of the light and area of reception is restricted in limited-reflective sensors. Therefore, objects are detected only at specified distance. Limited-reflective sensors are robust against changes in the colour of the sensing object but sensors operation is greatly delicate of inclination and glossiness of the object. [22]

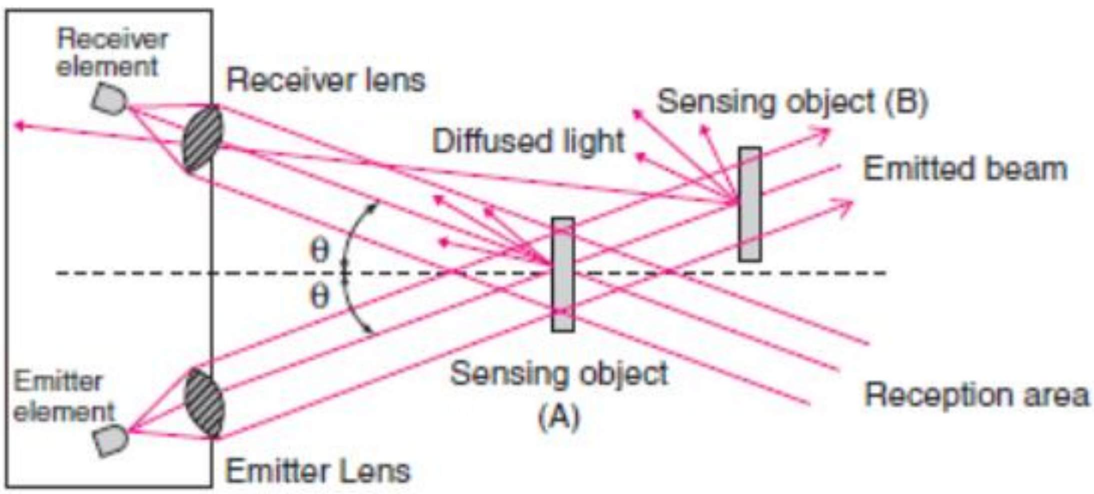

Figure 23. *Limited-reflective sensors can only detect objects in the overlapping area of light emission and reception [22].*

4.4.2 Through-beam sensors

Through-beam sensors consists of separate emitter and receiver units. Some models of through-beam sensors are called slot sensors, as they have an integrated emitter and receiver and a slot between them for a sensing object. Through-beam sensors provides better reliability compared to other types of photoelectric sensors, as there is near zero risk of unwanted reflections. They are also robust against contaminated environments and have relatively long sensing distances. [30,45]

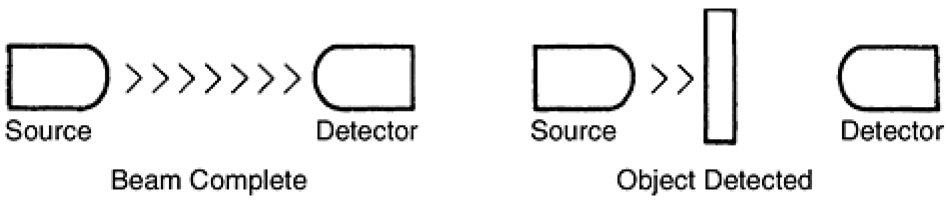

Figure 24. *Object detection with through-beam sensors [30].*

Diameter of emitted effective light beam is same size as the lenses on emitter and receiver. It takes about 80 % coverage of the light beam to trigger the sensor. [45]

4.4.3 Retro-reflective sensors

The basic structure of a retro-reflective sensor is similar to the diffuse-reflective sensor, where both emitter and receiver are located in one unit. Special reflectors are used with retro-reflective sensors to reflect the emitted light back into the sensor. Unlike mirrors, reflectors are designed to reflect the light directly back to the sensor even with inclination between sensor and reflector. When sensing object is positioned between sensor and reflector, light reflection is interrupted and therefore, the sensing object is detected. [26,30,45]

A polarized retro-reflective sensor is equipped with filters in front of the emitter and the receiver, that are in 90° phase difference with each other. These filters are used to polarize the light into single plane. Special depolarizing reflectors are used to depolarize the emitted light and to reflect it back into the receiver. This depolarized light passes through the filter in front of the receiver. If polarized light is reflected from the sensing object, it remains polarized. This polarized light cannot pass the filter in front of the receiver, as there is 90° phase difference between the reflected light and the filter. This ensures, that unwanted reflections will not be detected. Polarized retro-reflective sensors are used with highly reflective objects, ensuring reliable sensing data. [28,30,45]

4.4.4 Time-of-flight sensors

Time of flight sensors measure distances using elapsed time between the light emission and the reflection. As the light travels with a constant velocity, about $300 \cdot 10^6$ m/s in air, measured distance can be calculated with following formula:

$$x = \frac{t}{v}$$

where *x* is the measured distance, *t* is the time of flight and *v* is the velocity of the light [11,26]

Due to high velocity of the light, time of flight for emitted light pulses are extremely short, about 3 ns/m. Therefore, fast electronics are needed to measure short distances with reasonable resolution. This is not a problem with longer distances. However, the intensity of the reflected light decreases as the measurement distance increases. This problem emphasizes if the target surface is in inclination related to the sensor. Functionality of time of flight sensors on longer distances can be improved by using a retro-reflecting material on the target surface. [26]

Time-of-flight laser range finders uses pulse modulation, amplitude modulation or frequency modulation principle to measure distances. With a pulse modulation principle, the time of flight for one light pulse reflected to the receiver is measured. With an amplitude modulation principle, the phase difference of the emitted light and the reflected light are measured. With a frequency modulation, a range of frequencies are emitted and distance is estimated using the frequency of the reflection, that depends on the measured distance. Direct and coherent detection principles can be used with time-of-flight sensing. With a direct principle, signal power of the receiver is measured as a function of the time. With a coherent principle, target velocity can also be calculated using the phase information. [12]

Laser range finders using time-of-flight technology consists of laser emitter, one or two light receivers and timing discriminators, and a time measuring unit. Avalanche transistors are used in the laser emitter to produce short and powerful current pulses. The produced current is usually between 20-100 A and pulse time 3-10 ns. These current pulses are conducted to the semiconductor laser. [12]

Noises, changes in pulse form and amplitude, as also delay changes of optical and electrical signals causes measurement errors with time-of-flight distance measurement. Noises create changes between successive results, but delay changes impact results during long time periods with different measured distances. [12]

5. IMPROVEMENT OF SHUTTLE AND LIFT POSITIONING

The study for an improvement work started with an error analysis. A Visualization system used at the customer's site logs every error incident into a log file. This log file contains information about the error type, location of the error, start and ending time of the error and an additional information. This data was used to determine which shuttles and lifts had the most errors concerning positioning, and in which coordinate positions did these errors occur. If the same shuttle or lift had many issues with positioning, and especially if these issues occurred at the same coordinate position, there were some chronical error issues instead of a sporadic fault.

In most cases, errors with positioning has led only to short standstills and no damage to items or equipment. However, in some cases these mispositioned storage retrieval machines has led to crashes with totes stored in the warehouse system. Operating performance at the transfer position, where totes are transferred between shuttles and lifts, is essential. That is, as a mispositioned tote in the transfer position can lead into more serious malfunctions.

In chapter 5.1, the positioning process for shuttle is introduced in specific level. Subchapters introduces improvement methods for positioning precision. The positioning process for the lift is introduced in chapter 5.2 and improvement methods in subchapters.

5.1 Positioning of the shuttle

The maximum travel distance of a shuttle in x-direction of movement can be up to 150 meters, depending on the customer's specifications considering the length of the rack aisle. The maximum travel distance at the customer's site in this study is roughly 83 meters. The position of the shuttle is defined in a 2-dimensional space, where x-axis runs horizontally along rack aisle and y-axis vertically along different storage rack levels. 3rd dimension, z-axis, that runs horizontally, rotated 90° from x-axis (figure 9), has no effect on shuttle positioning and can be ignored in this case. That is, because only telescopic arms of the LHDs operate in z-axis direction of movement, and are only allowed to move after the shuttle has been successfully positioned.

The shuttle positioning is based on a reference position. This reference position for x-axis is located at the beginning of the rack aisle, and at the lower end of the y-axis for the hoisting unit. A retro-reflective photoelectric sensor is used to detect the x-axis reference point. This sensor is located at the bottom of the shuttle frame, and a reflector is connected to the lower rack rail of rack aisle (figure 25). The measurement data received from a forked light barrier sensor is also used to determine the reference position. This forked light barrier sensor is located next to the retro-reflective reference sensor. With the hoisting unit, an inductive proximity sensor is used to detect an y-axis reference point. This sensor is connected to the shuttle frame and is used to detect lower end of the hoisting unit.

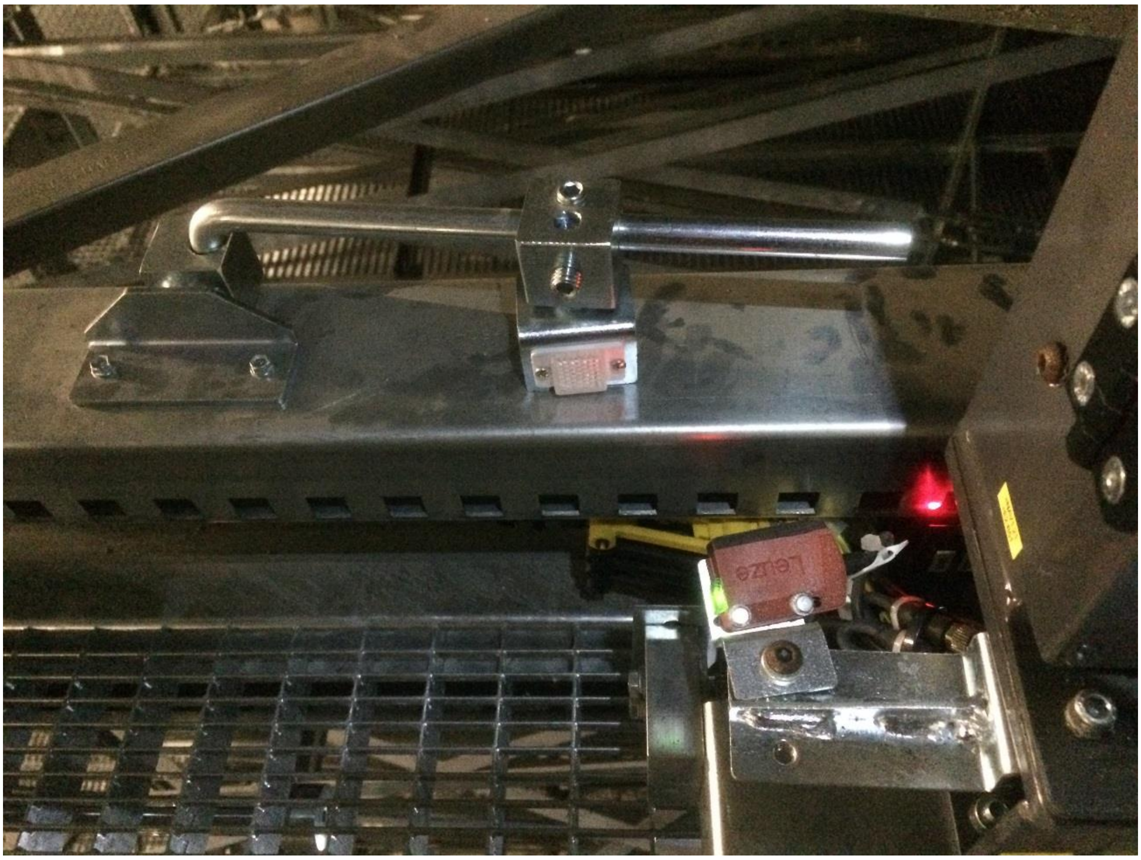

Figure 25. *The x-axis retro-reflective reference sensor and the reflector.*

The position of the shuttle in x-axis direction is measured with three different measurement systems: data received from the servo drive, forked light barrier, and fine-positioning sensors. Y-axis position is mainly measured with servo drive, and fine-positioning is implemented with fine-positioning sensors.

5.1.1 Servo drives

The x-master servo drive calculates current position of the shuttle by using a data received from the encoder of the x-master servomotor. This data is transmitted from the servomotor into the servo drive via encoder cable. However, encoder cables are vulnerable to electromagnetic interference (EMI). According to Stephens [39], disturbing signals get into a system via four paths: magnetic or inductive coupling, capacitive coupling from high-speed voltage changes, direct coupling and radiative or radiofrequency coupling.

Identifying the source of a disturbance on servo drives with feedback loops can be difficult. However, reduction of the electromagnetic interference is important to minimize errors on positioning.

Current and voltage feedback loops on servo amplifiers use relatively high gains and can easily amplify disturbances. Switch-mode power supplies operate at high frequencies, usually starting from 400 kHz. This can create problems with a capacitive and a radiofrequency type interference. The voltage sensor of the power supply may be interfered from the pulse width modulated output of the servo drive. The solution is to isolate the signals (encoder and power cables) with appropriate cable layout design and protective shielding. Especially high voltage sources, such as power cables and braking resistors need suitable protective shielding. Though the protective shielding is important, it does not remove the source of electromagnetic interferences. For positive results, the effect of these sources must be minimized. [39]

Radiofrequency type signals can be easily created. For example, electric arcs generate radiofrequency signals. This kind of problem is common in automobiles, where spark plugs and opening-closing relays cause radiofrequency interference. This disturbance interference nearby sensitive electronics and can cause unusual behaviour. Radiofrequency signals consist of two components: magnetic and electric components. Transmission between these components obeys following ratio:

$$\frac{\Delta U/\Delta t}{\Delta i/\Delta t} = \frac{\Delta U}{\Delta i}$$

where *U* denotes for voltage, *t* is time and *i* is current. [39]

Result of this equation represents impedance in the circuit. Impedance of the vacuum is around 376,73 Ω [20], and if this impedance is exceeded, a radiofrequency signal is transmitted through the free space. In addition, system needs antenna to transmit and receive radiofrequency signals and this can be any kind of a radiative surface, such as a metal plate. This surface emits magnetic and electric fields. [39]

Pulse width modulation signals can emit magnetic fields with relatively high power. In worst case, this magnetic field can conduct devices in the same circuit and even turn on nearby devices. The magnitude of this magnetic field can be affected with proper cables and shielding. Too long cables increase inductive load in the system and route of the cable has a significant effect on magnetic field emitted. In worst case, way too long cables are used between the servo drive and the servomotor, and these cables have been fastened on a tight roll with zip ties. Therefore, use of an approved and right length encoder, and power cables, that are well shielded and separated from each other is essential for appropriate servo drive performance. [39]

If the ground connection to the earth is not sufficient, a direct coupled interference signals can occur. This is common case in industrial power systems, where the safety ground and the neutral line are connected to the same potential. In a normal situation, the safety ground should never carry current and the neutral line carries the current. With shuttles, ground/neutral is conducted by a sliding contact conductor and an alternative ground is implemented by using a copper strip, that touches floor of the rack aisle. The sliding contact conductor rail is built by using sections that are connected to each other by using plastic connectors. These plastic connectors cause pressure against the lips of the sliding contact conductor rail and can cause gap between these lips to decrease. During movement of the shuttle, it can cause the conductor to rise from the conductor rail. This results in an insufficient contact with phase or neutral line. [34,39]

5.1.2 Fine-positioning sensors

As the power from the x-axis servomotors is transmitted via friction running wheels, the diameter, and the form of these running wheels effects positioning accuracy. Excessive wear on the running wheels causes the actual position to be different compared to the calculated one. However, the effects of the running wheels wear is already been taken into account by the factory. The second x-axis position measurement method is implemented by using two fork light barrier sensors. Leuze electronics GS 04 forked through-beam sensors are used [16]. Two of these sensors are located at the bottom of the shuttle frame. These sensors detect holes that are located on the lower guide rail in the rack aisle. This measurement data is not primarily used for positioning, but for reference. This reference data is compared to the position data calculated by the servo drive, and if there is a deviation of two or more holes, the PLC goes into error state. Due to this, this measurement system does not affect the positioning precision of the shuttle, but rather works as a supervisor for the servo drive.

Third x-axis measurement system is responsible for the fine-positioning of the shuttle. There are four laser diffuse-reflective light sensors located at the ends of the load handling devices. Same sensors are used for both x- and y-axis fine-positioning. Sensors on the LHD 2 (the upper one) are mainly responsible for the fine-positioning as the ones on the lower LHD 1 performs as a check-up. Fine-positioning sensors are used at the same side as the order tasks is being executed. These sensors have high switching frequency, 2 kHz for a fast and high precision applications. The scanning distance can be adjusted between 20-500 mm (a laser class 2), but this can vary significantly between different reflective surfaces, and alignment of these surfaces. With a maximum scanning range up to 250 mm, the black and white error stays under 10 %. If the scanning range is over 250 mm, the black and white error increases, and detection of different surface finishes on the same distance deteriorates. After distances of 250 mm, the detection of black surfaces deteriorates, as well after 400 mm for grey surfaces. The scanning behaviour between black and white surfaces can be seen from figure 26. It is notable, that after 250 mm scanning range, reduction of the scanning range on darker surfaces rises considerably. [17]

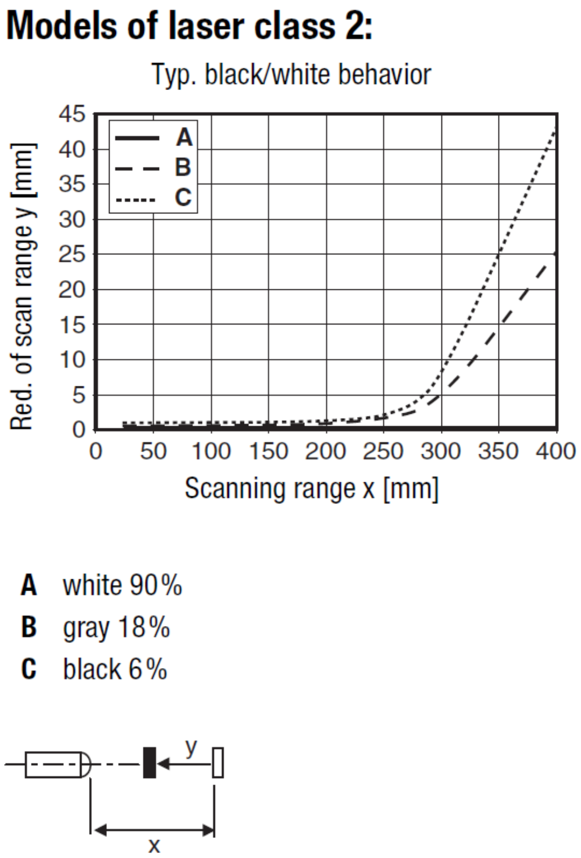

Figure 26. *The scanning behaviour between black and white surfaces [17].*

Exact sized fine-positioning holes are located on the lower rack rail on each storage and transfer area rack positions. When the shuttle receives a positioning order, it travels into that location by using the position data received from the servo drives. The fine-positioning procedure (figure 27) begins, when the shuttle detects the fine-positioning hole on the rack by the fine-positioning sensor at the calculated position in the x-axis. At this point, the shuttle shifts certain distance to the middle of the positioning hole. This distance is measured using the servo drive. After this, the shuttle drives the hoisting unit downwards until it detects the lower edge of the fine-positioning hole in the y-axis. At this point, the shuttle shifts certain distance upwards to the middle of the fine-positioning hole. As the actual position of the fine-positioning hole may differ from the theoretical one, it can take some extra time to locate the fine-positioning hole. This may be caused by a variation in the aisle rack tolerance, worn out or slipping running wheels, misalignment of the fine-positioning sensor, or lost or altered reference position data. If the actual position differs more than the limit specified in the PLC, a warning message is transmitted to the visualization software. Deviation in the actual position and the calculated one increases the operation time during the positioning task, because drive speed is reduced after the shuttle reaches desired calculated position. If the fine-positioning hole is not located at the calculated position, the shuttle starts moving in so called x-formation to locate the fine-positioning hole. If the fine-positioning hole is still unlocated, the PLC goes into error state. However, minor deviations may not bring the shuttle into a standstill. [46]

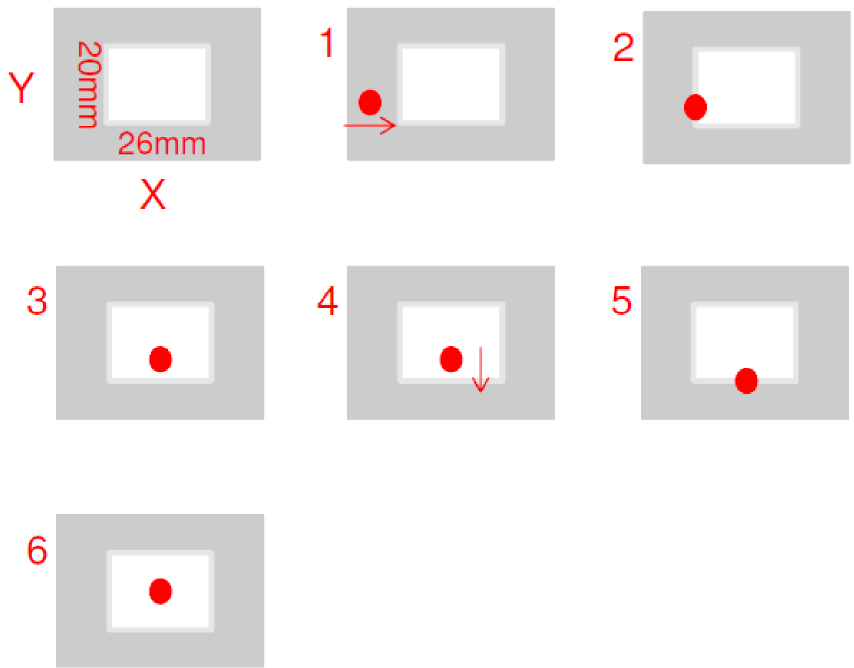

Figure 27. *The fine-positioning procedure. 1: Approaching the fine-positioning hole 2: Locating the edge 3: Taking the offset 4: Approaching the lower end 5: Locating the edge 6: Taking the offset [33].*

During this study became clear, that errors during the fine-position usually did not always correlate with deviations on the fine-position hole location. In most of the cases, there were interferences with the fine-positioning sensor. The sensor might have scanned posterior rack through the fine-position hole of the front rack. In other cases, sensor did not detect some parts of the front rack near fine-position holes. This was often the case at the transfer areas, where the fine-positioning hole was located in a separate metal plate glued onto the rack (figure 28). Sensor may not detect the intersection between rack and plate, causing the PLC to start taking the offset. During fine-positioning procedure, sensor detected the metal plate confusing the PLC. In response, PLC orders the shuttle to return into the section, where the edge of the fine-positioning hole presumably was [46]. In worst cases, the shuttle repeats this procedure, until going into error state. In optimal situation, the shuttle completes the fine-positioning process with a single try. A recommended solution to this, is to use wide plastic or metal plates with a fine-positioning hole, instead of ones that are currently used. New plates would be installed on the same side as the shuttle to rack rail. The plate should be over 100 mm wide, so that it covers the whole fine-positioning area (±50 mm from the fine-positioning hole).

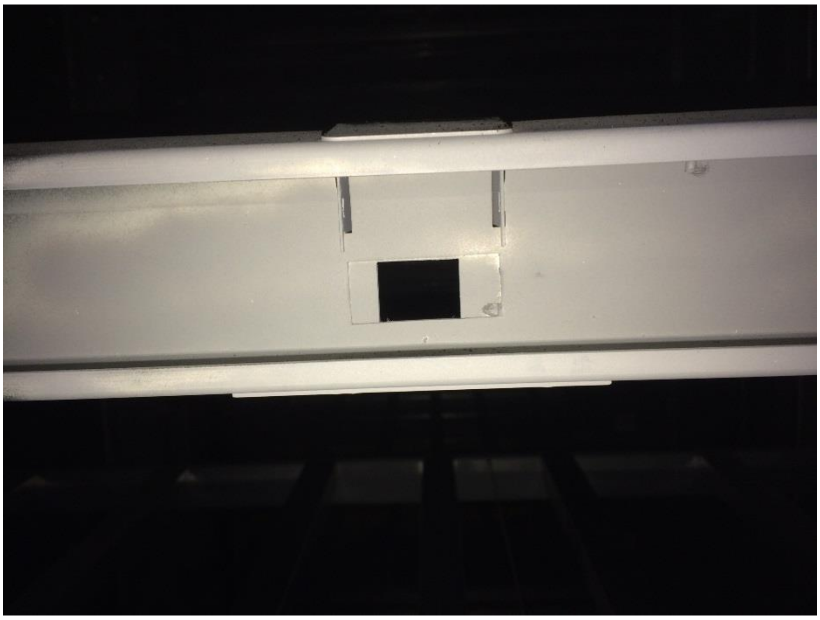

Figure 28. *An extra metal plate with fine-positioning hole with excessive adhesive in one corner. The area has been painted with non-reflecting grey paint, that is deteriorating the fine-positioning performance.*

5.1.3 Alignment of the sensor

For the fine-positioning sensor alignment work, the shuttle is taken out of the rack aisle into the maintenance bay area. At first, the offset and the alignment of LHDs and telescopes on each LHD are checked and corrected if necessary. The alignment of the shuttle frame is checked, as also level of LHDs. This is done by measuring distance from one telescope to the center of the LHD and to another telescope. [33]

An additional rack rail is installed to the maintenance bay area. The level of the rack rail is adjusted with a level. After this, fine-positioning sensor of the upper LHD light is focused on the center of the fine-positioning hole on the rack rail, and holding brake of the x-axis servomotor is switched on to prevent unwanted movement of the shuttle. The horizontal offset to the lower LHD is checked by driving the hoisting unit upwards, until the light of the fine-positioning sensor on the lower LHD is in the middle of the fine-positioning hole vertically. The horizontal offset of the sensor light to the center of the hole is measured and corrected if necessary. The rollers on the LHD should be on the same level as the rack rail. Interferences with the sensor are usually caused by glossy surfaces either on the scanning range or in the background. To avoid unwanted interferences from the background, the sensor should be mounted in a slight inclination angle (5…7 °), so that the receiver is further away from the target than the emitter [17]. During study became apparent, that alignment of fine-positioning sensors varied distinctly. Some were aligned facing straight towards rack, while some were aligned in positive or negative inclination angle. [33]

The previous procedure is “the official” way to align the fine-positioning sensor. However, the lack of vertical offset measurement must be taken into account. Also, if the sensor alignment work is done when storage racks are already filled with totes, an offset deviation might occur between storage totes and shuttle LHDs. These downsides led to development of an easier and a faster way to check the alignment. During this study, shuttles with the worst fine-positioning behaviour were inspected. Sensors were aligned with a proper inclination and with a near-zero offset between two sensors on the same operating side. The scanning range of sensors were adjusted by testing different settings to ensure proper function.

Wear of the support rollers of the shuttle increases the inclination of the shuttle frame. This causes the load handling device to tilt. As the fine-positioning sensors are connected to load handling devices, this increases vertical offset of sensor alignment on different sides of the shuttle. The proper level of the shuttle should be verified regularly.

Sensors were exposed to different amount of unwanted reflections in different rack locations. It was noted during this study, that the operation in worst reflecting rack locations can be improved by painting rack rails in the background with non-reflecting paint. Foremost rack rails should have a reflecting and a smooth surface.

As a result to these procedures, operation of these problematic shuttles improved significantly. An analysis based on the error log data and remarks of service technicians verified the results. In best cases, fine-positioning errors on specific shuttle was reduced by 100 %, and the monthly downtime was reduced by over 11 hours. Following tables 1-5 represents error logs on some worst operating shuttles before and after the sensor alignment work. Total error finger and telescope errors are caused by finger or telescope crashing the tote due to misalignment of the fine-positioning sensor. Finepos timeout and rackfine sensor errors are caused by insufficient operation of the fine-positioning sensor. In the tables, *n* stands for the number of incidents, *min. t* is minimum standstill time caused by individual incident, *max. t* is maximum standstill time caused by individual incident, and *total t* is the total standstill time of all the same types of error incidents.

__Table 1.__ Shuttle 5112 positioning related errors before and after sensor alignment.

5112: 01.08.2016 - 01.09.2016	**n**	**Min. t**	**Max. t**	**Total t**
LHD2: Total error finger 2 Tel 2 left: 2	29	0.00:01:51	0.00:41:03	0.06:05:50
LHD2: Total error telescope 2	27	0.00:00:19	0.00:25:12	0.04:18:03
LHD2: Total error finger 1 Tel 1 left: 2	4	0.00:05:10	0.00:14:50	0.00:33:36
LHD2: Timeout positioning telescopes	4	0.00:01:30	0.00:09:25	0.00:20:13
LHD2: Total error finger 6 Tel 2 right: 1	1	0.00:13:19	0.00:13:19	0.00:13:19
LHD2: Total error telescope 1	1	0.00:08:27	0.00:08:27	0.00:08:27

5112: 01.11.2016 - 01.12.2016	**n**	**Min. t**	**Max. t**	**Total t**
LHD2: Total error finger 2 Tel 2 left: 2	0	0.00:00:00	0.00:00:00	0.00:00:00
LHD2: Total error telescope 2	0	0.00:00:00	0.00:00:00	0.00:00:00
LHD2: Total error finger 1 Tel 1 left: 2	0	0.00:00:00	0.00:00:00	0.00:00:00
LHD2: Timeout positioning telescopes	0	0.00:00:00	0.00:00:00	0.00:00:00
LHD2: Total error finger 6 Tel 2 right: 1	0	0.00:00:00	0.00:00:00	0.00:00:00
LHD2: Total error telescope 1	0	0.00:00:00	0.00:00:00	0.00:00:00

__Table 2.__ Shuttle 4116 positioning related errors before and after sensor alignment.

4116: 01.08.2016 - 01.09.2016	**n**	**Min. t**	**Max. t**	**Total t**
Y-Timeout finepos	30	0.00:00:26	0.00:33:09	0.02:41:18
X-Timeout finepos	30	0.00:00:26	0.00:33:09	0.02:41:18

4116: 01.11.2016 - 01.12.2016	**n**	**Min**	**Max**	**Total**
Y-Timeout finepos	0	0.00:00:00	0.00:00:00	0.00:00:00
X-Timeout finepos	0	0.00:00:00	0.00:00:00	0.00:00:00

__Table 3.__ Shuttle 2217 positioning related errors before and after sensor alignment.

2217: 01.08.2016 - 01.09.2016	**n**	**Min**	**Max**	**Total**
X-Rackfine sensor LHD1 right	14	0.00:00:12	0.00:10:06	0.01:28:17
Y-Rackfine sensor LHD1 right	1	0.00:00:40	0.00:00:40	0.00:00:40
Y-Timeout finepos	1	0.00:08:52	0.00:08:52	0.00:08:52

2217: 01.11.2016 - 01.12.2016	**n**	**Min**	**Max**	**Total**
X-Rackfine sensor LHD1 right	0	0.00:00:00	0.00:00:00	0.00:00:00
Y-Rackfine sensor LHD1 right	0	0.00:00:00	0.00:00:00	0.00:00:00
Y-Timeout finepos	0	0.00:00:00	0.00:00:00	0.00:00:00

Table 4. Shuttle 1215 positioning related errors before and after sensor alignment.

1215: 01.10.2016 - 01.11.2016	n	Min	Max	Total
Y-Timeout finepos	19	0.00:00:17	0.00:12:06	0.01:17:18
X-Timeout finepos	18	0.00:00:17	0.00:12:06	0.01:16:52
X-Rackfine sensor LHD2 right	9	0.00:00:41	0.00:40:03	0.01:09:08
X-Rackfine sensor LHD1 right	3	0.00:00:48	0.00:02:50	0.00:04:49

1215: 01.11.2016 - 01.12.2016	n	Min	Max	Total
Y-Timeout finepos	1	0.00:02:30	0.00:02:30	0.00:02:30
X-Timeout finepos	0	0.00:00:00	0.00:00:00	0.00:00:00
X-Rackfine sensor LHD2 right	0	0.00:00:00	0.00:00:00	0.00:00:00
X-Rackfine sensor LHD1 right	0	0.00:00:00	0.00:00:00	0.00:00:00

Table 5. Shuttle 1218 positioning related errors before and after sensor alignment.

1218: 01.10.2016 - 01.11.2016	n	Min	Max	Total
Y-Timeout finepos	6	0.00:00:33	0.00:15:36	0.00:32:49
X-Timeout finepos	6	0.00:00:33	0.00:15:36	0.00:32:49
X-Rackfine sensor LHD2 right	1	0.00:11:20	0.00:11:20	0.00:11:20

1218: 01.11.2016 - 01.12.2016	n	Min	Max	Total
Y-Timeout finepos	1	0.00:01:21	0.00:01:21	0.00:01:21
X-Timeout finepos	1	0.00:01:21	0.00:01:21	0.00:01:21
X-Rackfine sensor LHD2 right	0	0.00:00:00	0.00:00:00	0.00:00:00

In table 1, the shuttle 5112 was having issues with misaligned fine-positioning sensors causing offset on load handling devices. This caused LHD1 to set tote in different position in x-axis during storing compared to LHD2. As LHD2 was retrieving tote, that was stored by LHD1, this offset caused telescopes to hit the tote. The operation of this shuttle was improved by reducing the offset between fine-positioning sensors on the same side by sensor alignment.

In tables 2-5, shuttles had issues with completing the fine-positioning process. Y- and X-timeout fine-positioning errors occurs, when the shuttle has not been able to complete the fine-positioning process in given time. Rackfine sensor errors are caused by malfunctioning fine-positioning sensors. The operation of these shuttles were improved with sensor replacement, sensor alignment and sensing distance adjustment, and by improving the surface finish on the transfer areas.

Improvements for currently used fastening for the fine-positioning sensor is also recommended. Currently sensor is fastened with one screw only with multiple washers. Current configuration is noted to be sensitive and the sensor can easily be misaligned. The sensor alignment would be implemented with lockable screws, that would allow easy and fast alignment work, but with robust design.

5.1.4 The fine-positioning sensor check-up function

Cause of the misalignment during the fine-positioning process and crashing between LHD telescopes and totes were frequently caused by the difference of the fine-positioning sensor alignment with different LHDs of the shuttle. This was noted by remarks of service technicians. Difference in the sensor alignment between lower and upper LHD leads to offset difference during storing tasks. If a tote is stored and retrieved with different LHD, risk of collision increases. Trivial solution to this is to check the fine-positioning sensor alignment on every single shuttle frequently. Yet this kind of operation consumes huge amount of working time (about half an hour per one shuttle, according to service technicians), it does not completely remove sensor problems. Sensors can get misaligned during service work or during a collision with warehouse items.

During this thesis study an idea of an automated sensor check-up function stand out. As the PLC receives real time position data from the servo drives, this data can be used for this kind of function. Advantages of this kind of automatic check-up function are lack of extra machinery needed, short runtime compared to manual sensor alignment inspection, and possibility to schedule automatic check-ups during idle time.

The idea of this check-up function is to use two storage rack locations with known locations in a 2-degree of freedom coordinate system. The most logic option is to use storage rack heights y2 or y3 on both sides of the rack aisle, that are closest to the maintenance bay area door. The check-up function would follow the same procedure as used in the fine-positioning process (figure 27). The first stage of the check-up function is to reference axes of the shuttle. The second stage is to locate the edge of the fine-positioning hole of the reference storage rack location by approaching from left in x-axis direction. The third stage is to drive the hoisting unit down in y-axis direction until the lower edge of the fine-positioning hole is detected. Same procedure is done for both load handling devices and on both sides of rack aisles. As a result, the difference of the fine-positioning sensor alignment on both sides of the shuttle is known in x- and y-axis directions. In optimal situation, offset in x-direction is zero and offset in y-direction is the height of storage rack level. If difference of these values is higher than tolerances set, a sensor realignment work needs to be done. The basic steps of this check-up function can be seen in figure below.

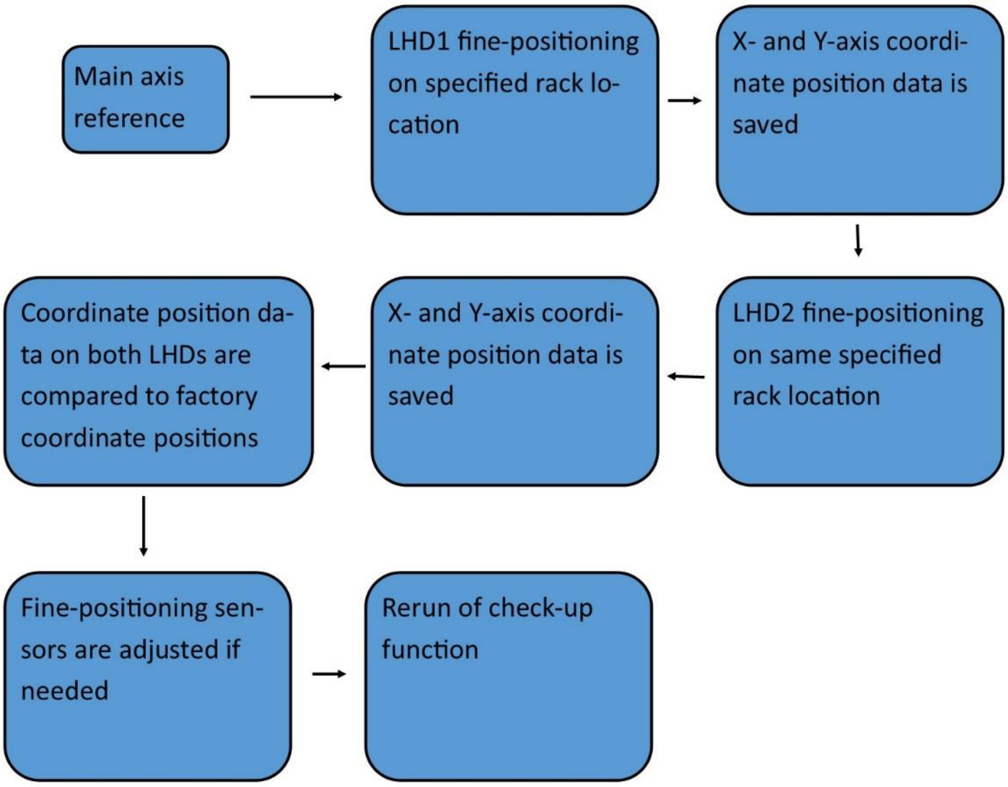

Figure 29. *The fine-positioning sensor check-up function process proposed in this study.*

This check-up function could be implemented manually or automatically. In manual implementation, function works in a PLC level only. Service technician can run the check-up function from the PLC and the measured difference is shown on display. In automatic implementation, the function is connected into the visualization software. Therefore, the check-up function can be scheduled for idle times and a warning message is sent in case of excess deviations. The measurement data can also be reported and compared to previous and default values.

5.1.5 Alternative options for fine-positioning sensors

Standard sensors used for the shuttle fine-positioning are Leuze electronics HRTL 3B Laser diffuse-reflective sensors with a background suppression. The sensor uses pulsed light, with wavelength of 650 nm [17]. The emitter of the sensor uses laser (light amplification by stimulated emission of radiation [27]) as the source of light [17]. Photoelectric diffuse-reflective sensors are also available with different kind of light emitters with different wavelengths. [26,34]

Diffuse-reflective sensors are available with wide range of different features. Sensors with different light sources, wavelengths or pulse frequency are available. Leuze electronic offers vast variety of these sensors with compatible cable connectors. This allows easy testing with different sensor types, without need of rewiring. Light emitters used in Leuze electronics sensors are mainly a LED and a laser, and wavelength is mainly in a visible area. Some sensors with infrared area wavelengths are also available, but sensor alignment can be difficult without visible pilot light.

Remarks during this thesis study indicated, that most of the current fine-positioning sensors were working properly. Some individual malfunctioning sensors had signs of impacts on the cover lens. It was noted, that even slight cracks on the cover lens can cause irrational sensor operations. These cracks tend to alternate angle of light coming to the receiver. This can cause the sensor to not detect nearby objects, but at the same time posterior background could be detected. As a result, more robust sensors with stainless steel housing are recommended. Use of external sheet metal cover for the sensor is also recommended, in order to reduce unintentional hits to the sensors from different objects.

Alternative types of photoelectric sensors were also considered. Retro-reflective sensors allow more inclination in sensor alignment. Therefore, risk of unwanted reflections from background can be reduced. Robustness against unwanted reflections can be even greater, when polarized retro-reflective sensors are used. However, retro-reflective sensors require special reflectors. Further analysis showed, that acquiring and installing these reflectors to each rack locations would not be economically reasonable. In addition, retro-reflective sensors do not offer same precision as diffuse-reflective sensors. Also, vast number of reflectors along rack aisles could possibly compromise operation of nearby sensors in shuttles and lifts. Through-beam sensors offer sufficient precision for automated machinery. Use of through-beam sensors was rejected at the beginning, due to high cost and need for massive installation and wiring work. Other alternative sensor systems, such as machine vision, and robotics proximity sensors were considered too expensive.

5.1.6 Alternative options for main axis sensors

During this thesis work, possibility of main axis positioning improvements was studied. An accurate and reliable main axis position data would make use of fine-positioning sensors unnecessary. As the positioning deviations mainly occur on the x-axis only, improvement of the x-axis position measurement is only necessary. As the x-axis servo drive data is not accurate due to reasons introduced in chapter 5.1.2 and front light barrier sensors are only used to detect major deviations, an accurate x-axis measurement sensor is needed. As this sensor must be able to measure distances reliably and accurately in distances up to 150 m, number of suitable sensor options is low.

As use of mechanical distance sensor is hard to implement, one plausible solution is to use time-of-flight photoelectric distance sensor. This sensor would be connected to the shuttle frame and a flat, reflective sensing surface would be connected to the rack aisle, or vice versa. If the sensor would be connected to the rack aisle, it would be less vulnerable to vibration and collisions. However, the reflecting surface must have certain diameter and with distances up to 150 m, diameter of the reflecting surface could be too large to be installed to shuttle.

Sensor manufacturer SICK offers a selection of time-of-flight distance sensors with measuring range up to several hundred meters. Dx100 product family for example has a distance sensor capable to measure distances up to 200 m with ±2,5 mm accuracy and 1 mm repeatability. However, fine-positioning sensors are able to detect objects with thickness larger than 150 µm [17]. This leads to reduced accuracy, assuming that fine-positioning sensors are properly aligned. [29]

5.2 Positioning of the lift

Positioning of the lift is based on the data received from the y-axis servo drive. This data is compared to the reference position, which is implemented by a mechanical sensor. Leuze electronics HRTL 3B sensors are used for the fine-positioning in rack levels. Positioning in inbound and outbound conveyors is ensured with Leuze electronics PRK 25B retro-reflective sensors. It must be considered, that this sensor is not used for the fine-positioning, but for ensuring proximity of the lift to the conveyor. I.e. correct fine-position related to conveyors is only based on the servo drive data. [18]

As the hoisting unit of the lift is connected to a counterweight with two hoisting belts that are operated by the servomotor, wear, stretch or vibration of the hoisting belts affects the positioning accuracy. If there is an excessive deviation with the defined transfer area position and the actual position, the positioning procedure becomes slower or an error occurs. This is due to the extra time used by the lift to locate the fine-positioning hole.

The lift fine-positioning procedure is only used in y-axis direction of travel, as the lift does not operate in x-axis direction. This results in more simple fine-positioning procedure, compared to the fine-positioning process of the shuttle. However, based on the error log data, some individual lifts are more sensitive to fine-positioning errors than others. During this study, possible error causes were identified.

5.2.1 Alignment of the sensor

As the lift does not operate in x-axis direction, only LHD telescope alignment effects on the x-axis positioning. As a conclusion, lift telescope alignment should be checked with each shuttle connected to concerned lift aisle. However, each lift co-operates with 8 or 16 shuttles, and each shuttle co-operates with 9 lifts, acquirement of proper alignment is demanding.

During this empirical study, most fine-positioning errors on the lifts were caused by misaligned or incorrectly adjusted fine-positioning sensors. Sensors with too much or too few inclination either in horizontal or vertical direction were responsible for errors, as they caused unwanted reflections. Lifts with a y-axis fine-position deviation were more likely to cause errors. If there is deviation on both working sides of the lift, the real position value can be altered from the control panel of the PLC. If the deviation only occurs on one working side only, the cause of error is more likely related to sensor alignment or mechanical deformation of the chassis of the lift. As lifts did not suffer from excess positioning deviations in y-axis deviation, improvement of y-axis distance measurement is not seen necessary.

As part of this work, fine-positioning sensors on some worst operating lifts were aligned and sensing range adjusted to minimize unwanted reflections. In some cases, the sensor was replaced. As a result, standstill time on individual lifts was reduced significantly. On the lift 4086 monthly standstill time was reduced over 24 hours. Tables 6 and 7 containing positioning related errors on lifts 4086 and 5088 can be seen below.

Table 6. *Lift 4086 positioning related errors before and after sensor alignment.*

4086: 01.11.2016 - 01.12.2016	**n**	**Min**	**Max**	**Total**
Y-Timeout finepos	86	0.00:00:08	0.09:41:50	1.01:27:55

4086: 01.12.2016 - 01.01.2017	**n**	**Min**	**Max**	**Total**
Y-Timeout finepos	1	0.00:00:48	0.00:00:48	0.00:00:48

Table 7. *Lift 5088 positioning related errors before and after sensor alignment.*

5088: 01.08.2016 - 01.09.2016	**n**	**Min**	**Max**	**Total**
Y-Rackfine sensor LHD1 right	12	0.00:00:07	0.10:12:04	0.10:51:04

5088: 01.11.2016 - 01.12.2016	**n**	**Min**	**Max**	**Total**
Y-Rackfine sensor LHD1 right	0	0.00:00:00	0.00:00:00	0.00:00:00

In table 6, the lift 4086 was having issues with completing the fine-positioning process during the given time. One main reason was excessive vertical inclination of the fine-positioning sensor. The operation of the sensor can vary distinctly with different sensor alignments. This is most likely to be caused by c-form rack rails, where fine-positioning holes are located. As the shuttle is approaching the fine-positioning hole horizontally from x-axis direction, the fine-positioning sensor is only detecting flat metal surface (see figure 28). The lift is approaching the fine-positioning hole vertically in y-axis direction. This causes the fine-positioning sensor of the lift to detect different inclinations and edges of the rack rail during the fine-positioning process. Excessive vertical inclination of the fine-positioning sensor can cause different operation, depending if the lift is approaching the fine-positioning hole from the below or above. If the c-form rack rail would be facing the other way around, this issue would be cleared.

In table 7, the lift 5088 was having issues with the malfunctioning right side fine-positioning sensor. For the fine-positioning sensors used in lifts, same improvements are recommended as for shuttles in chapter 5.1.3.

5.2.2 The fine-positioning sensor check-up function

As with the shuttles, the sensor check-up function can also be implemented with lifts. The first step is to reference the y-axis by driving the lift to the reference position. After the reference, the lift drives to the upper position with relatively slow speed, measuring fine-positioning hole positions during the travel. This position data is saved and it can be compared to reference data. If there is constant error on either working side of the lift, there is most likely an alignment error with the fine-positioning sensors. If the error is sporadic, error is more likely caused by deviation in rack formation or malfunction with the encoder of the servomotor. Constant error on both working sides can be corrected by alternating position data from the PLC or by adjusting reference sensor position.

6. CONCLUSIONS

The aim of this thesis was to study properties of logistic automation systems and sensor technology. This information was used to improve the positioning operation of shuttles and lifts in the multi-level automated warehouse system.

The level of automation used in logistics operations is growing. This trend started with automating transport operations in warehousing with conveying systems and automated guided vehicles. To increase the efficiency of logistics operations even more, implementation of fully automated warehouses increases. Typically, these warehouses are based on high bay or other kind of storage rack system used for storing totes or pallets. Workers are used to decant and pick items from storage totes or pallets, that are transported from the warehouse to the workers automatically. In some fully automated applications, even decanting and picking processes are automated. Development of warehouse control and management systems increases level of autonomy in logistics operations.

Growing level of automation and autonomy also increases requirements of sensor technology. As the attendance of humans in different processes decreases, level of consideration, or so called “common sense” also decreases. This can be improved with better sensor technology.

In this master’s thesis study, properties of different sensor technologies and their convenience in studied use were compared. Also, different methods to improve operation of current sensors were covered in this thesis work. As a result, different sensor options for fine-positioning or main axis position measurement were introduced, as also sensor check-up function for easier sensor alignment work.

Fine-positioning sensor check-up function proposed in this study would operate in PLC level, using position data received from servo drives to determine fine-positioning sensor alignment deviations compared to factory values. Deviations in sensor alignment would be shown for service technician in control panel display. In case of excessive deviation, service technician would realign sensors and perform sensor check-up function again to confirm proper sensor alignment. Implementing this proposed sensor check-up function would save significant amount of time, as manual sensor checking and realignment work for one shuttle takes approximately half an hour. Execution time for reference and fine-positioning processes in this check-up function would be completed in a few minutes. Therefore, only shuttles and lifts with misaligned sensors would be needed to check and readjust manually. Saved working time would be even greater, if visualization software based automatic implementation would be used.

Procedures implemented during this thesis study improved fine-positioning performance well, as can be seen in tables 1-7 in chapters 5.1.1 and 5.2.1. Development of introduced sensor check-up function is recommendable, as use of this function would make sensor alignment work easier and faster for service technicians. For different sensor options, properties of different photoelectric sensors were studied. However, operation of currently used sensors can be improved with proper sensors alignment and optimizing reflectivity of the rack rails. Painting the foremost rack rail with glossy light paint and posterior rack rail with non-reflecting paint improved the operation of diffuse-reflective fine-positioning sensors. Considering for different options for main axis position measurement improvement was also recommended, as this would eliminate the need for separate fine-positioning sensors.

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